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A CASE STUDY OF A COMBAT AIRCRAFT'S
SINGLE HIT VULNERABILITY

by

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September 1986

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A Case Study of a Combat Aircraft's Single Hit Vulnerability

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

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September 1986

ABSTRACT

This thesis presents the methodology for a detailed vulnerability assessment of a generic aircraft in the conceptual/preliminary design stage. The single hit vulnerability of the aircraft to a 100 grain fragment is determined using the textbook, The Fundamentals of Aircraft Combat Survivability Analysis and Design. The intent of this work is to provide a realistic case study of a vulnerability assessment that can be used by others as a learning tool.

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To my wife Mary, and children Patrick and Kathleen, thank you for understanding the long hours and absences. I can say for sure that without your love and support none of this would have been possible.

I. INTRODUCTION

"The survivability of an aircraft operating in an enemy threat environment depends on its design and on the emphasis placed on its survivability throughout its life cycle. The cost of modern aircraft weapons systems, the aircraft and personnel attrition experienced in recent combat, and the resulting loss of operational capability make survivability enhancement imperative." This paragraph is in the forward of MILITARY STANDARD 2069/AS (MILSTD 2069), Requirements for Aircraft Non-Nuclear Survivability Programs [Ref. 1:p. iii]. This document establishes the guidelines between the contractor and the Department of Defense (DoD) regarding survivability design in major weapons systems. Its primary thrust is that survivability must be a design requirement, one that is incorporated and implemented from the conceptual design phase through the total life cycle of a major weapons system.

The survivability design discipline has only recently become a major factor in weapons acquisition. Dr. R.E. Ball, Professor of Aeronautics at the Naval Postgraduate School (NPS) in Monterey, California recognized the importance of aircraft survivability in a hostile threat environment more than ten years ago. What began as a set of notes for a course taught at NPS has evolved into The

Fundamentals of Aircraft Combat Survivability Analysis and Design [Ref. 2]; the first textbook that fully examines the total survivability picture from both the design and analysis points of view. Dr. Ball's book is the basis for the following case study in the vulnerability of an aircraft in the conceptual/preliminary design phase.

The author, following the words of Dr. Ball [Ref. 2:p. 11], "survivability must seriously be considered by everyone during the early design phase of the aircraft"; chose to do a vulnerability analysis of an aircraft of his own design. This aircraft was designed to fulfill the requirements of AE-4273, Aircraft Conceptual Design, a graduate level aeronautics course taught at the Naval Postgraduate School.

The course material is based on a seminar in conceptual design given by Mr. D.P. Raymer of Rockwell International. The course develops the aircraft design based on a given, generic Request For Proposal (RFP) for an attack aircraft. The aircraft was developed using historical data, "rules of thumb", current aeronautics trends, and regression equations. The component layouts and structural arrangements were conceived by the author using current tactical aircraft designs as guidelines. The resulting conceptual design was then analyzed with respect to aeronautical and operational capabilities. Lift curves, drag polars, weights, and other performance parameters were determined

to establish compliance with the requirements set forth by the RFP.

The author's design represents a generic aircraft, one in which the systems, structures, capabilities, and performance are unclassified. By conducting a vulnerability assessment of this generic, conceptual design, the author hopes to obtain the widest dissemination of this critical design consideration.

Prior to discussion of this topic, it should be stated that this case study is based soley on the methodology presented by Ball [Ref. 2]. The author assumes the reader is very familiar with this methodology, or has the reference readily available. The specifics of Dr. Ball's book will not be repeated here, the reader is left to refer to the text as necessary for any background clarification. In each succeeding chapter, references are made to pages, figures, etc., to assist the reader. (Although the author feels that this case study could stand alone to someone intimately familiar with aircraft combat survivability, the language and methods of this engineering discipline are somewhat unique and further guidance and reference is sometimes very helpful.)

II. CONCEPTUAL DESIGN OVERVIEW

The acquisition process for a major weapons system is a lengthy and costly one. From initial analysis to full scale production, the time period may span ten or more years. It is imperative that everything possible is done to ensure that the system is the most "effective" one that industry and the government can produce.

Department of Defense Instruction 5000.2 (DoDINST 5000.2) [Ref. 3] is the primary guideline for the Major System Acquisition Process. Figure 2.1 [Ref. 4:p. ICD-1] shows the tasks and Milestones that must be met in order to satisfy all of the DoD requirements for the production of a major system. Figure 2.2 [Ref. 4:p. ICD-2] presents the different acquisition cycle interrelationships that are conducted simultaneously in order to meet the Milestones required by DoDINST 5000.2 [Ref. 3]. The conceptual/preliminary design phase activities are required to be completed between Milestones 0 and 1.

By the time Milestone 0 has been completed, the following has been accomplished with regard to system development:

1. A threat has been identified and a system to counter the threat has been proposed. The Defense Intelligence Agency has validated the threat and made the DoD aware of the shortfalls of existing systems in meeting the threat.

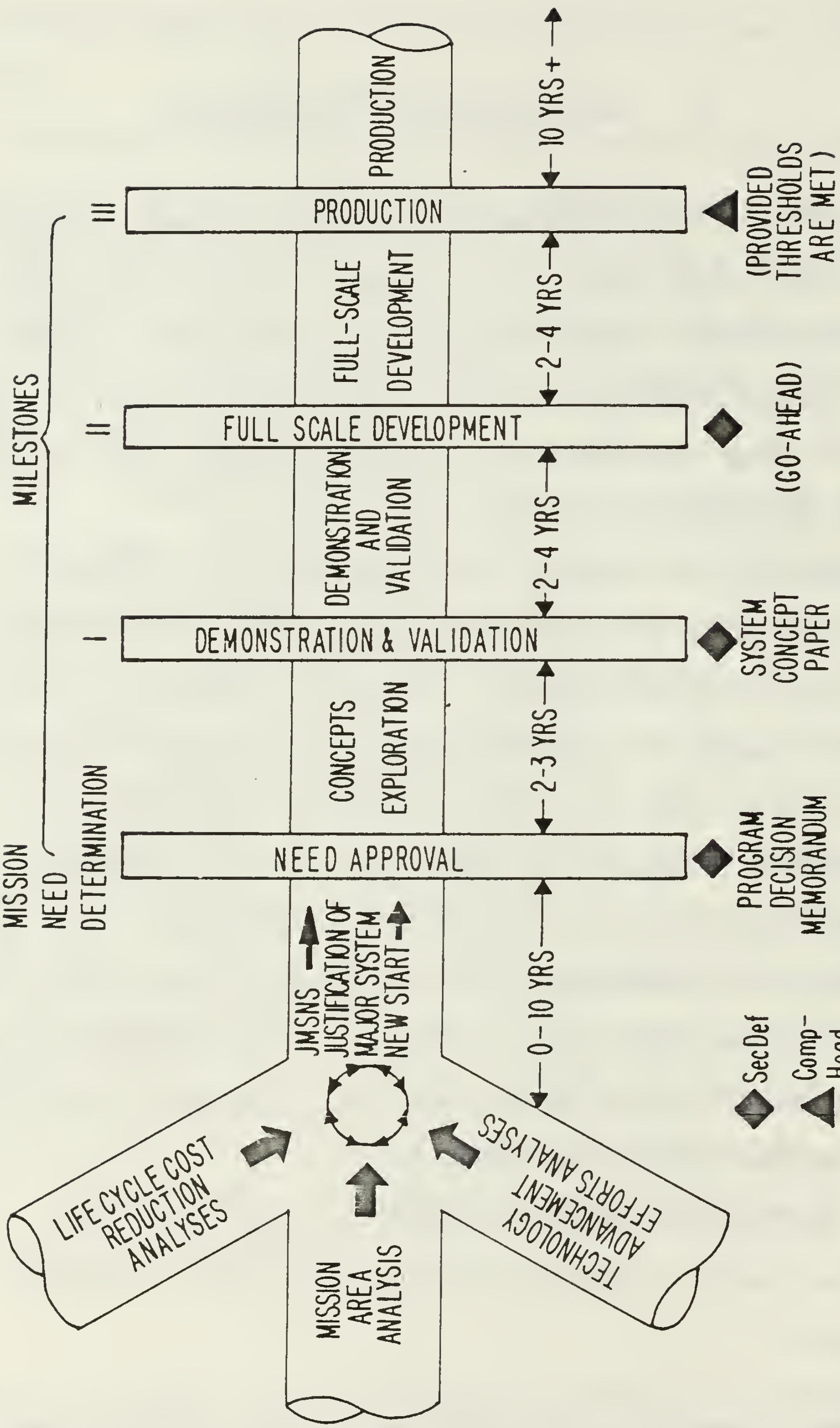


Figure 2.1 Major Systems Acquisition Milestones

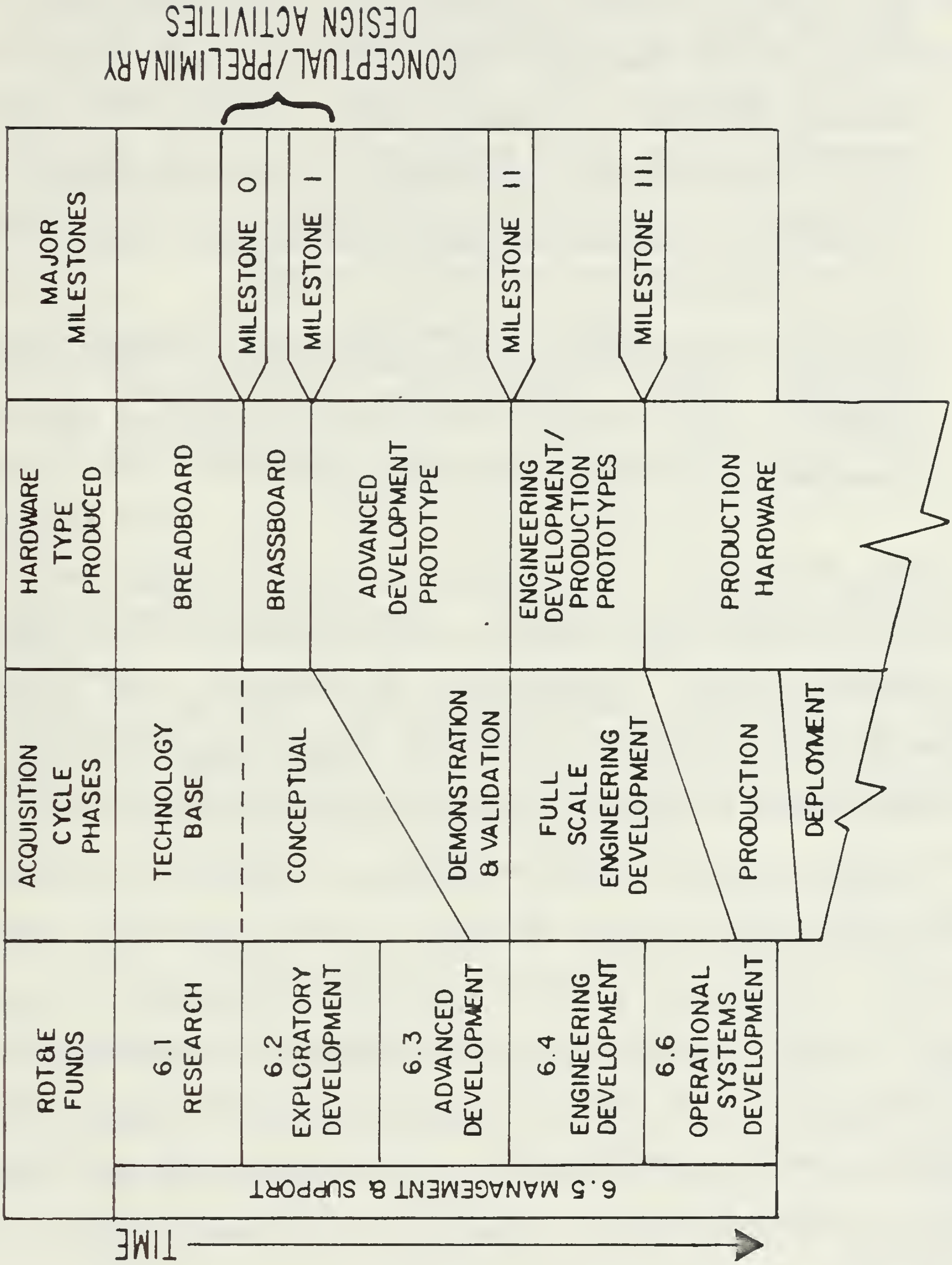


Figure 2.2 Acquisition Cycle Interrelationships

2. The Department of Defense responds with a Request For Information (RFI) to the defense industry. This is a document soliciting concepts for the system the DoD feels it needs to counter the expected threat. The RFI will specify the boundary conditions to be looked at in the early development of the system, such as survivability, logistics, costs, standardization to existing systems, etc.. Industry in turn, responds to the DOD's requirements with an estimation of the technological feasibility of building the system to fulfill its intended use. This system is based on historical data, engineering trends, and future hardware capability estimates.

3. DoD looks at industry's response, and if satisfied, requests a Justification of Major Systems New Start, or JMSNS. Here, approval from the Secretary of Defense is required to continue research and development into the new system. Once that approval is received, Milestone 0 has been met.

After Milestone 0 has been met, DoD once again makes a request to industry to submit ideas or proposals for the new weapons system. The Request for Proposal (RFP) is used by the industry to develop its conceptual systems design. The time period between Milestone 0 and Milestone 1 is usually two to three years as shown in Figure 2.1. The RFP is much more detailed and specific in its guidelines than the RFI. It relays to industry specifically what the weapons system must be capable of doing to eliminate the expected threat. It provides guidelines with regards to categories such as aerodynamics, performance, size, weight, mission, weapons/armament, carrier suitability/field performance, survivability and crew considerations. Industry then uses this document as the baseline data for its conceptual/ preliminary designs. The generic design

process is shown in Figure 2.3. This table breaks down the design process into three phases of development. For the purpose of this case study, the aircraft design is assumed to be between phases two and three of the design process.

The importance of a survivability assessment in the conceptual/preliminary design phase cannot be overemphasized. As seen in Figure 2.3, each phase of the design process requires a corresponding survivability analysis. It is a requirement that is noted in every guideline to contractors for major weapons systems. For example, MILSTD 2069 [Ref. 1:p. 1] states:

> "A standard must be developed in the early stages of major systems acquisition. A survivability assessment program is to be included in each contractural work statement. The purpose of this is to require studies, threat definitions, and contractural trade-offs to allow contractors to propose conceptual or notational designs which will meet combat survivability demands and generate data upon which firm design requirements will be based for full scale engineering development."

From an economic standpoint alone, the government should demand conceptual trade-off studies using survivability assessment methodology. It is much easier, and much more cost effective, to change a design while in the "paper phase", than to attempt to modify an existing airframe. The assessment in the conceptual/preliminary phase provides an opportunity to examine the effects of changes in the parameters and the design. How these changes

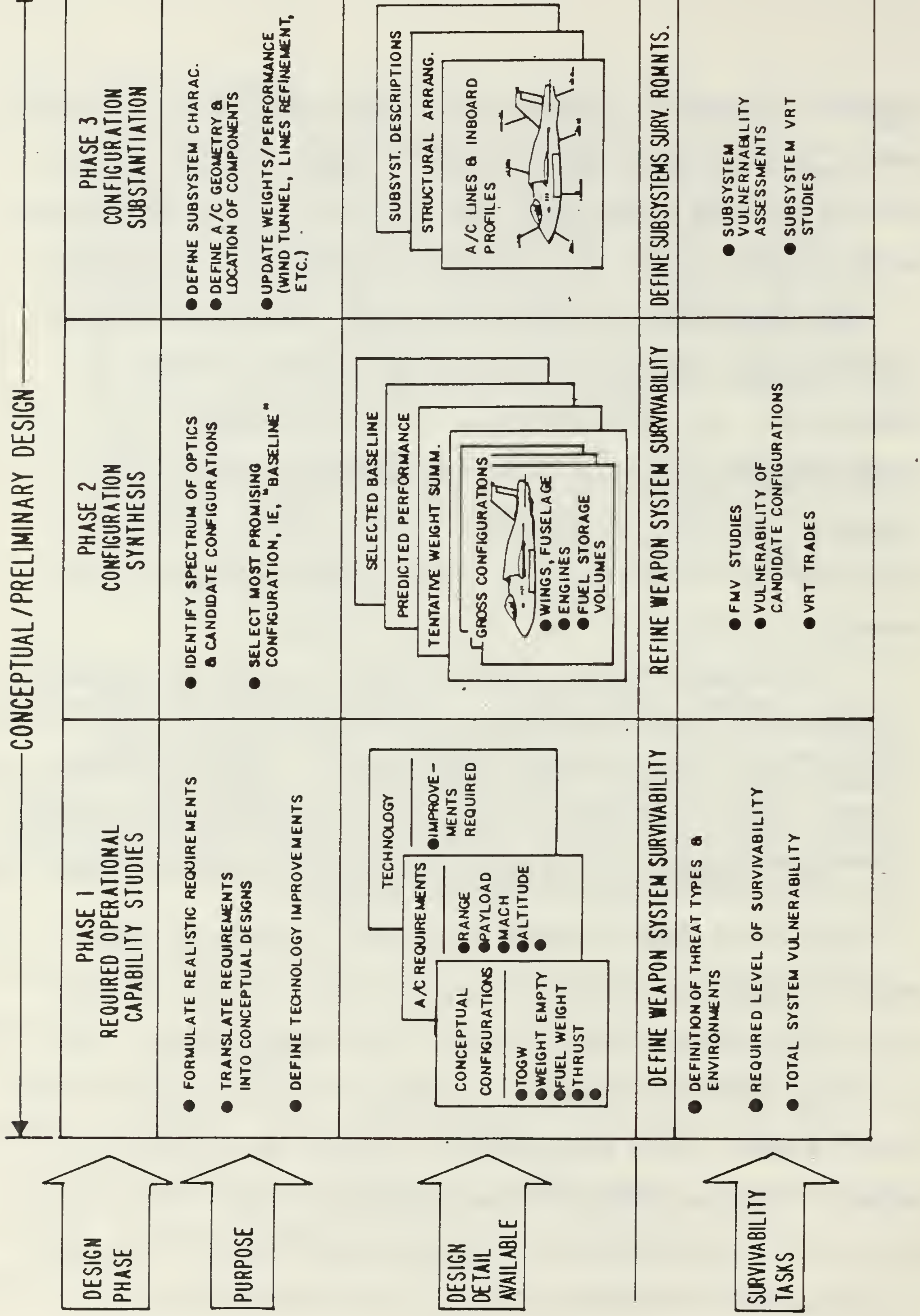


Figure 2.3 Generic Design Process

affect the aircraft's survivability, performance, tactics, maintainability, reliability, armament and cost can be evaluated and assessed with regards to the benefits and penalties. The following chapter will introduce the survivability program and the steps necessary for its implementation and completion.

III. <u>SURVIVABILITY PROGRAM OVERVIEW</u>

The contractor for a major weapons system must establish a DoD approved Survivability Program and integrate it into the company's management system. Ball [Ref. 2:p. 34], states:

> "To develop a survivable, cost-effective aircraft requires a systematic survivability program beginning in the conceptual phase and continuing throughout the life cycle of the aircraft. It is essential that survivability criteria be established early in the conceptual phase and that alternative designs and utilization solutions be developed. By developing this information before the final design configuration is established, the most cost effective survivability enhancement techniques can be identified."

MILSTD 2069, <u>Requirements for Aircraft Non-Nuclear Survivability Programs</u> [Ref. 1], is the standard the DoD uses to provide uniform requirements and guidelines for establishing survivability programs. Figure 3.1 [Ref. 1:p. 2] shows the life cycle of a typical survivability program. It shows that survivability is a continuous process that begins in the initiation phase and continues throughout the life cycle of a weapons system.

The survivability of an aircraft is related to two fundamental attributes, susceptibility and vulnerability. The susceptibility of an aircraft can be defined as the inability of the aircraft to avoid being hit while conducting its mission. It is dependent upon how well the

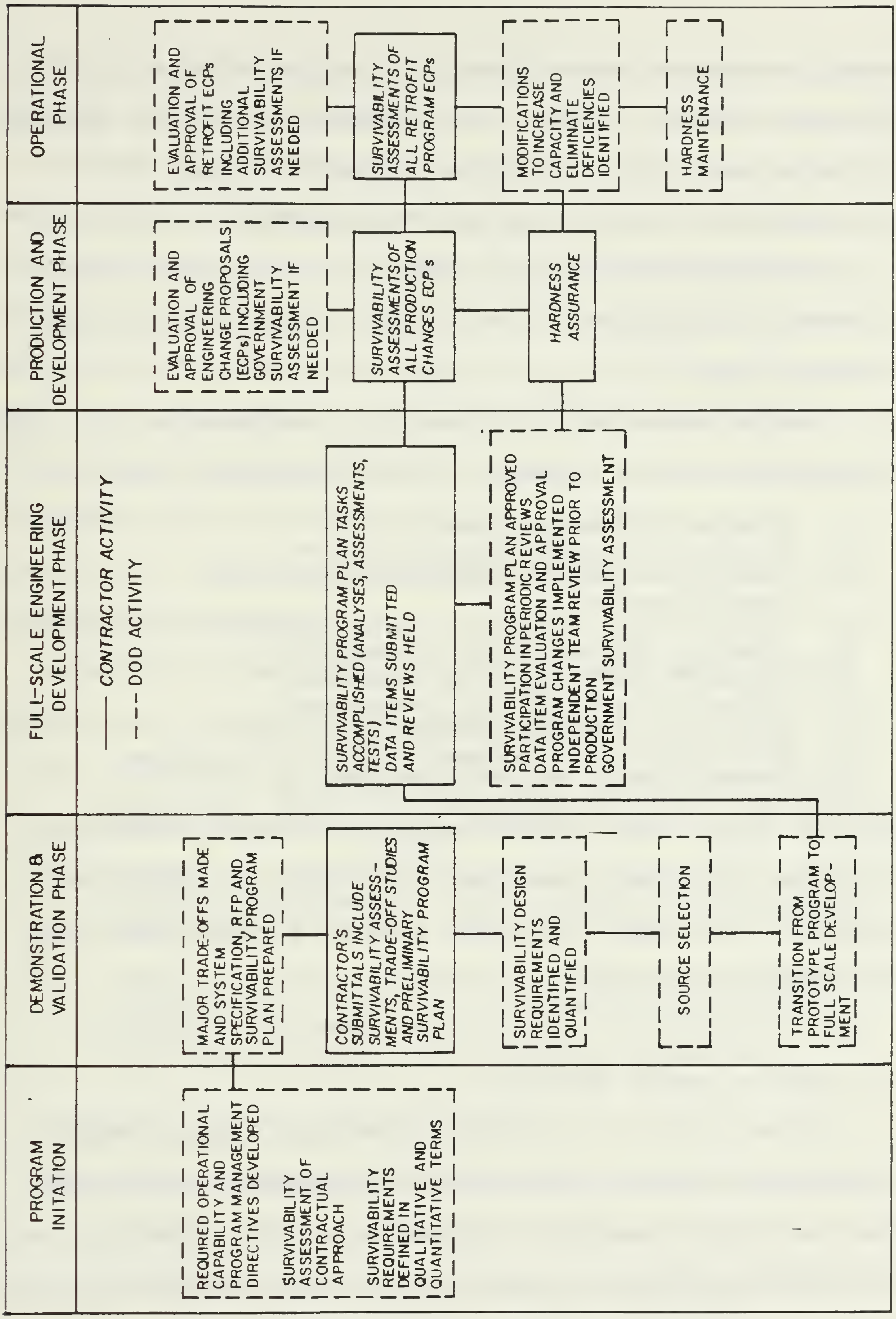


Figure 3.1 Survivability Life Cycle

enemy is able to detect, identify, track, acquire, and hit the aircraft as a target. The vulnerability of an aircraft is the measure of how much the system or systems are degraded due to the hit by the damage causing mechanisms. A survivability program is concerned with all the design factors that influence the aircraft's susceptibility and vulnerability.

MILSTD 2069 [Ref. 1:pp. 12-25] defines the following tasks that must be included in a survivability program:

1. Mission Threat Analysis
2. Aircraft Geometric Configuration
3. Flight and Mission Essential Functions Identification
4. Failure Mode, Effects, and Criticality Analysis
5. Aircraft Vulnerability Assessment
6. Aircraft Susceptibility Assessment
7. Aircraft Survivability Assessment
8. System/Cost Effective Analysis
9. Survivability Enhancement Trade-Off Studies
10. Combat Damage Repair Assessment

Most of these tasks will be explained in a general manner according to MILSTD 2069 [Ref. 1]. Then, in subsequent chapters, the first five tasks will be accomplished using the generic aircraft.

A. MISSION THREAT ANALYSIS

The missions of the aircraft and the expected threat systems are expressed in the DoD generated specifications such as the RFI and RFP. The expected flight profiles and defense situations that the DoD has identified are used to develop designs and conduct trade-off studies.

The contractor attempts to define each operational mode in terms of aircraft performance, weights, armament, etc., to meet the expected threat scenario that has been given as the basis for the design. Encounter conditions should be determined and used as the basis for survivability design and trade-off studies. These studies are used to ensure the aircraft can operate effectively in the threat environment. It is important to identify all possible threats the aircraft may encounter during a mission. If the aircraft is capable of a multifunction role, then the expected threats will vary according to the situation and the environment the aircraft is in.

According to Ball [Ref. 2:p. 115], the Mission Threat Analysis can be divided into three phases:

(1) Define the mission and the flight envelopes of the aircraft. This will encompass operating environments, mission types and flight conditions.

(2) Define the expected threat environment for each mission and theater. Here the enemy systems are analyzed to determine their envelopes.

(3) Combine the data gathered in the first two phases. Estimate the likelihood of encounter between the aircraft and each threat system, and identify the conditions of each at the time of encounter.

B. AIRCRAFT GEOMETRIC DESCRIPTION

The aircraft geometric description is the development of a detailed, accurate description of the aircraft for use in the vulnerability analysis. For an aircraft in the

conceptual/preliminary design phase, as much technical and functional data as possible must be collected on each major system of the aircraft. This data should include, but need not be limited to:

1. engineering drawings
2. trade-off study results
3. 3-view scale drawings
4. narrative descriptions of the proposed systems
5. block diagrams
6. flow charts
7. projected performance data
8. cross section drawings

For an aircraft currently in the inventory, its NATOPS and MIMS could be added to this list to provide a thorough description of the aircraft, its systems and operating capabilities.

For aircraft being analyzed using current computer programs for single hit vulnerability (see Ball [Ref. 2:p. 192-198]), this collected data is used to generate a geometric model and descriptor of the aircraft and its systems. This model is then used with the computer programs to develop vulnerability indices for the aircraft. Such a task is beyond the scope of this case study.

C. FLIGHT AND MISSION ESSENTIAL FUNCTIONS

Using the missions defined by the DOD, the contractor must determine the flight and mission essential functions for each mission phase. A flight essential function is that function performed by one or more components on the

aircraft which permits the aircraft to sustain flight through adequate lift, thrust and control.

A mission essential function is a function performed by one or more components on the aircraft that permits it to accomplish its defined mission. For example, the weapons delivery system of an attack aircraft is not a mission essential function during the take-off, climb-out or cruise phases of a flight. But it is definitely a mission essential function during an ordnance delivery run on a designated target.

D. FAILURE MODE, EFFECTS, AND CRITICALITY ANALYSIS (FMECA)

The Failure Mode, Effects, and Criticality Analysis (FMECA) is a multidiscipline design procedure, utilizing design inputs such as system reliability, maintainability, and safety to define the response of the aircraft and its systems to damage caused by the damage mechanisms. As such, it is one of the most important parts of the vulnerability assessment. The ultimate goal of this analysis is to identify the aircraft's critical components. A critical component is defined as one whose damage or loss could lead to an attrition level or mission abort level kill.

Utilized in the conceptual design phase, MILSTD 2069 [Ref. 1:p. 13], defines the FMECA as a procedure that:

(1) Documents all possible potential failures for each component or subsystem.

(2) Determines by prediction and analysis the effect of each of the failures on system operation.

(3) Identifies potential failures critical to personnel safety.

(4) Ranks each failure according to effect severity.

The FMECA procedure is performed in two steps, (1) a Failure Mode and Effects Analysis (FMEA) and (2) a Damage Mode and Effects Analysis (DMEA). Another analysis tool,not formally required by MILSTD 2069 is the Fault Tree Analysis (FTA). This can be used in addition to, or in place of, an FMEA if one is not available.

1. <u>Failure Mode and Effects Analysis (FMEA)</u>

Figure 3.2 [Ref. 1:p. 15] shows the role of the FMECA in the overall vulnerability assessment. In the FMEA phase:

(1) The contractor must identify, to the best of his theoretical and analytical ability, all possible failures and their effects on the aircraft.

(2) Each critical component is identified and its functions defined.

(3) All possible failures of the component are examined, including those due to its location within the aircraft.

(4) The results of these failures must be related to the components own functional ability and also to the functional abilities of the system from which that component is a part. This in turn, is related to effects of component damage in the overall aircraft.

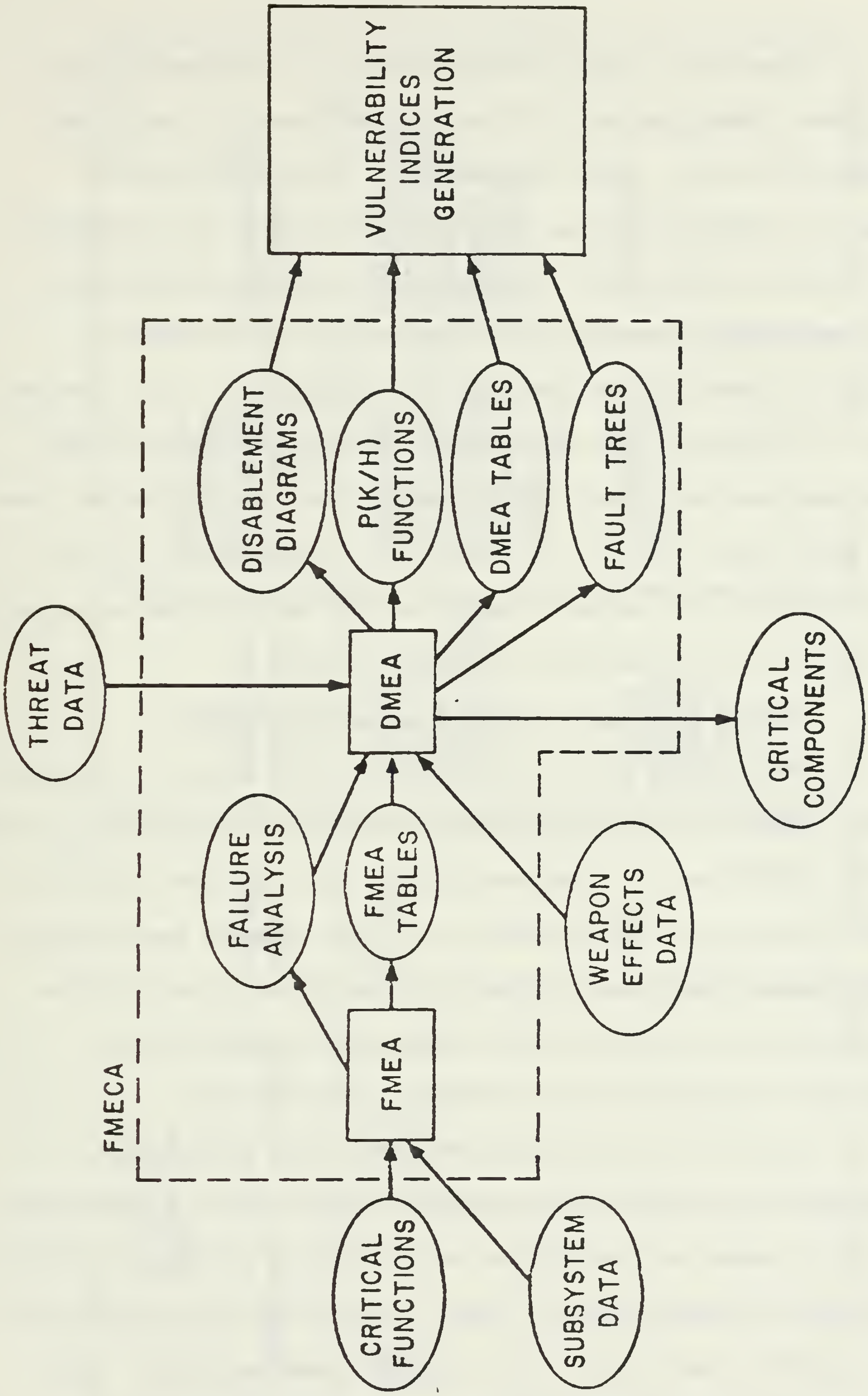


Figure 3.2 Interfaces of the FMECA Process

The major input to the FMEA is the physical and functional description of the aircraft and its systems, components, etc.. This information is the Aircraft Geometric Description as discussed earlier. The output of the FMEA is usually in the format of a self-explanatory table or matrix (Figure 3.3) [Ref. 2:p. 142]. The contractor must be as specific as possible to the current level of design. For the conceptual/preliminary level, major systems and some basic components can be broken down into sufficient detail to provide a thorough analysis. In later stages, the actual "nuts and bolts" of the components are examined for possible failure modes.

2. Damage Mode and Effects Analysis (DMEA)

The second part of the FMECA, the DMEA, is related to and dependent upon predicted damage from exposure to the combat environment. The contractor must assess the component's potential failures due to the damage mechanisms, relate these failures to the kill level required in the assessment, and quantify the component's ability to continue to operate in the hostile environment.

The kill level referred to in the previous paragraph can be any one of three categories of aircraft kill that measure the degree to which the aircraft suffers performance degradation. These categories are attrition kill, mission abort kill and forced landing kill. The attrition kill is the one most commonly analyzed, and

SUBSYSTEM		FAILURE MODE	EFFECT ON SUBSYSTEM	EFFECT OF DEGRADED SUBSYSTEM ON AIRCRAFT	AIRCRAFT KILL CATEGORY
COMPONENT	LOCATION				
ROD 3127	LEFT WING	SEVER	AILERON GOES TO HARDOVER (UP) POSITION	HARDOVER EFFECT CAN BE BALANCED WITH OTHER CONTROL SURFACES	AIRCRAFT CAN FLY AND LAND USING OTHER CONTROL SURFACES
		JAM	PILOT'S CONTROL STICK IS LOCKED	NO CONTROL OF FLIGHT	ATTRITION

Figure 3.3 Example FMEA Format

is a measure of the severity of aircraft damage that causes it to be lost from the inventory. Time is the most important parameter in the attrition kill, therefore it is the basis for the four levels of attrition kill. These levels are:

1. KK kill: Damage that will cause an aircraft to disintegrate immediately upon being hit.

2. K kill: Damage that causes an aircraft to fall out of manned control within 30 seconds after being hit.

3. A kill: Damage that causes an aircraft to fall out of manned control within 5 minutes after being hit.

4. B kill: Damage that causes an aircraft to fall out of manned control 30 minutes after being hit.

The A level or 5 minute attrition kill is the kill level usually used by DoD and industry to evaluate the vulnerability of an aircraft. The A level attrition will also be used for this case study.

The DMEA relies heavily on information gained from a correct and thorough FMEA. The DMEA also identifies any secondary damage caused by the primary damage mechanism. For example, a secondary fire caused by the detonation of an HEIT projectile inside the aircraft's structure. Ball [Ref. 2:p. 145] provides a table (Table 3.1) of the most important damage caused failure or kill modes of the major systems. Each system mentioned is broken down in the DMEA and analyzed to determine the lowest level of component failure.

TABLE 3.1 SYSTEM DAMAGE-CAUSED KILL MODES

Fuel	Propulsion	Flight Control
Fuel supply depletion	Fuel ingestion	Disruption of control signal path
In-tank fire/explosion	Foreign object ingestion	Loss of control power
Void space fire/explosion	Inlet flow distortion	Loss of aircraft motion data
Sustained exterior fire	Lubrication starvation	Damage to control surfaces and hinges
Hydraulic ram	Compressor case perforation or distortion	Hydraulic fluid fire
Power Train and Rotor Blade/Propellor	Combustor case perforation	
Loss of lubrication	Turbine section failure	**Structural**
Mechanical/structural damage	Exhaust duct failure	Structure removal
	Engine control and accessories failure	Pressure overload
Electrical Power		Thermal weakening
Severing or grounding		Penetration
Mechanical failure	**Crew**	
Overheating	Injury, incapacitation, or death	**Avionics**
		Penetrator/fragment damage
	Armament	Fire/explosion/overheat
	Fire/explosion	Radiation damage

Because the DMEA analyzes the criticality of failure, the output from the study is more detailed and elaborate than from an FMEA. The DoD will notify the contractor on the required DMEA data necessary for the particular weapons system being assessed. The depth of detail and breakdown will depend on which design phase the assessment takes place in.

There are four sets of data which make up the DMEA output. The first set is the DMEA Matrix or Table (Figure 3.4) [Ref. 1:p. 17]. The contractor must break down the aircraft systems to their component level; and relate these components and their failure modes to the probability of kill given a hit P(k/h) functions, kill level, and redundancy levels. In a conceptual/preliminary design phase, the contractor uses historical data and predicted engineering specifications of materials and components to make this analysis.

The second type of data produced from an DMEA is a Disablement Diagram. Figure 3.5 [Ref. 2:p. 144] is the graphical representation of the results of the FMEA and DMEA. The contractor uses the system design proposals and predicted survivability of each component to graphically illustrate the failures of the system to a specified kill level.

AIRCRAFT ____

SYSTEM FLIGHT CONTROLS (MECHANICAL)

FMEA REF ____

COMPONENT NAME	COMPONENT NUMBER	DISABLEMENT DIAG. NO.	DAMAGE MODE	"KILL" CATEGORY: NON REDUNDANT ATTRITION	NON REDUNDANT MISSION ABORT	NON REDUNDANT VERTICAL	REDUNDANT ATTRITION	REDUNDANT MISSION ABORT	REDUNDANT VERTICAL	REMARKS	$P_{k/h}$ FUNC. NO.
STICK			BREAK OR DISABLE								
ASSEMBLY										DEGRADED	
(GRIP)	3001				X					FLIGHT CONTROL	32
		1									
			LOSS OF ELECTRICAL							LOSS OF CAS PITCH AND	
CAS SENSOR	3002		CONNECTIONS		X		X			ROLL CONTROL	32
		2	(LOSS OF CAS)							CONTROL THROUGH DEL.	
			LOSS OF ELECTRICAL							REVERSION TO MECH. (IF DEL	
			AND MECHANICAL	X	X					IS LOST). (DEL = DIRECT	
			LINKAGES							ELECTRICAL LINK)	
RUDDER PEDALS	3006		BREAK OR DISABLE								
ARMS	3007		ONE ARM								32
SUPPORT	3008	3									32
FEEL SPRING SUPPORT	3301		BREAK OR DISABLE								32
SPRING	3302		SUPPORT, FEEL							NO ELECTRICAL	32
TRANSDUCER	3303		SPRING ASSY, OR	X	X					INPUTS TO	24
			TRANSDUCER							RUDDERS	

Figure 3.4 Example DMEA Matrix

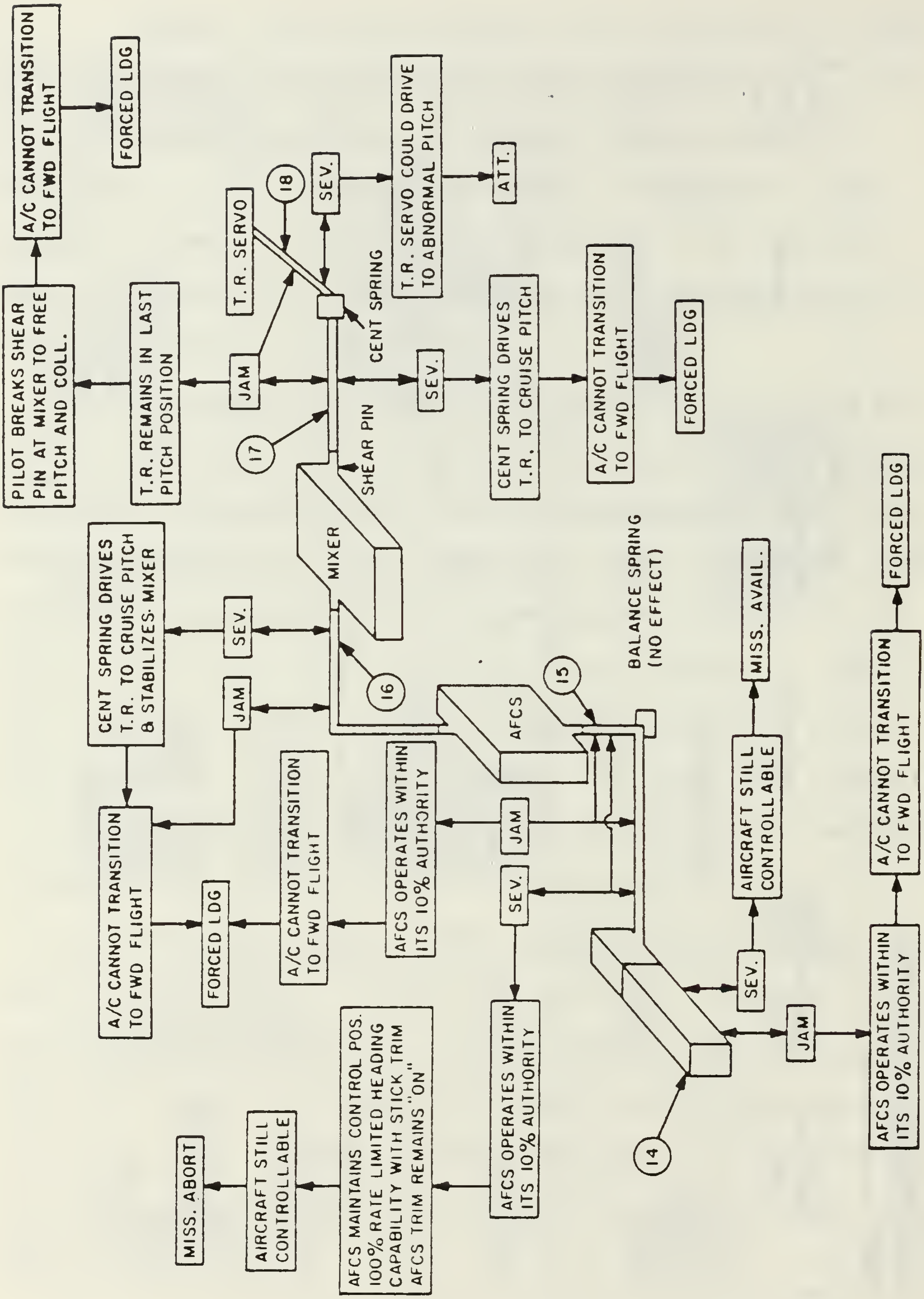


Figure 3.5 Example Disablement Diagram

The third set of data generated by a DMEA is the Kill Tree or Kill Diagram. The Kill Diagrams are developed by combining data from the Flight and Mission Essential Functions Analysis, FMEA, DMEA, Disablement Diagrams, and should include evaluation by members of the operational community and engineers responsible for the design of the aircraft. They are a function of kill level and graphically depict the combination of components and systems that must be sufficiently degraded to effect the particular kill level on the aircraft.

The kill diagram is a visual illustration and identification of the critical components of the aircraft and their redundancy relationships. It is constructed by the contractor for the aircraft in a specific flight condition. The example kill diagram shown in Figure 3.6 [Ref. 2:p. 153] illustrates the effect of redundancy on a system.

The last data source of the DMEA is the set of "probability of kill, given a hit" functions (P(k/h). These functions, or values are assigned to a component based on its response to being impacted by a damage mechanism (fragment or projectile). The contractor normally uses government provided or specified P(k/h) values where required. In a conceptual/preliminary design phase the contractor also uses historical data and available ballistic test data to ascertain the amount of damage the component will sustain. The P(k/h)

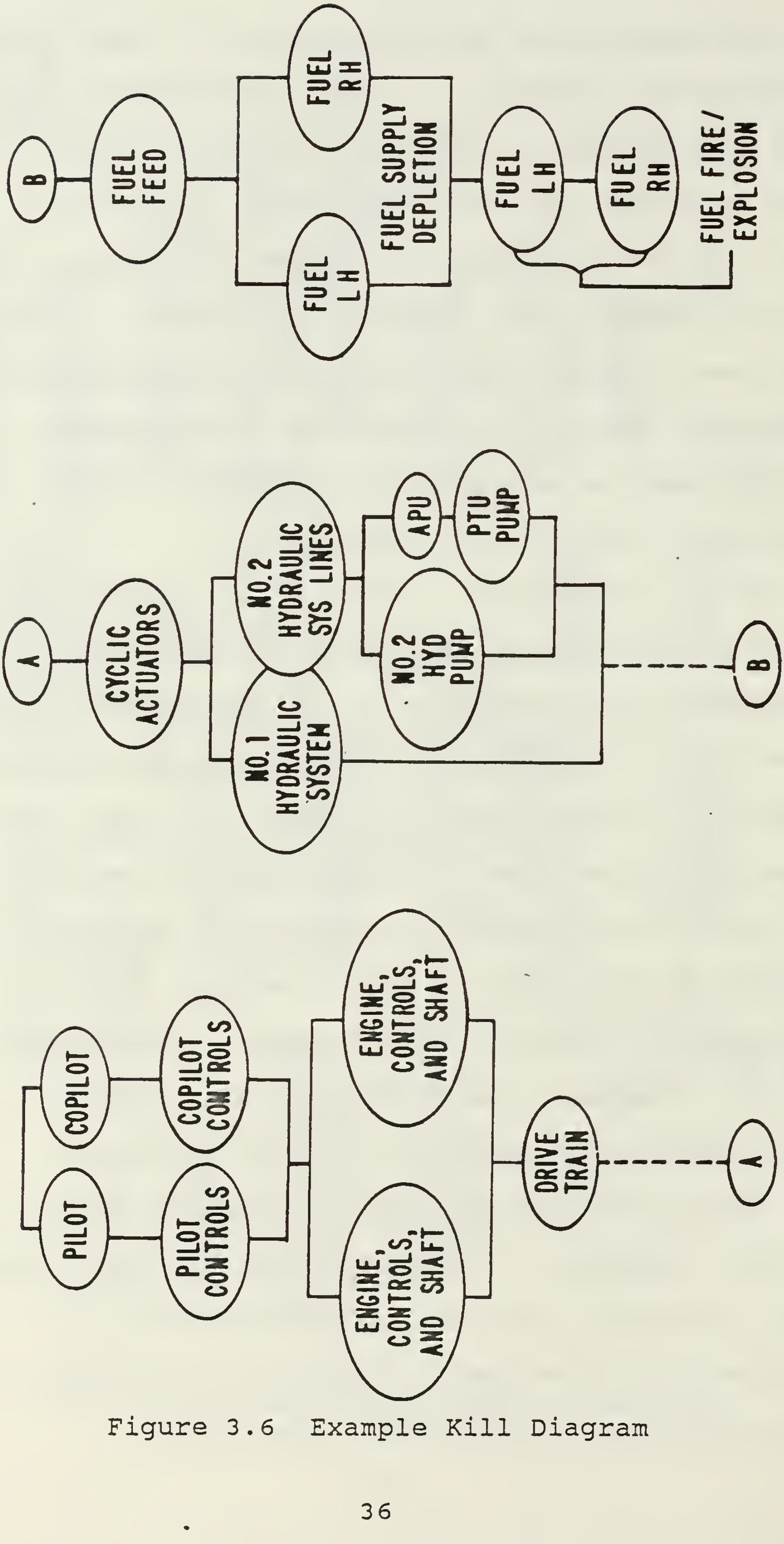


Figure 3.6 Example Kill Diagram

for each component requires sound engineering judgement and realistic design assessments. The functions can be expressed graphically as a function of damage mechanism mass and velocity (Figure 3.7) [Ref. 2:p. 156], or in analytical format. The contractor uses the P(k/h) functions for components that can be killed by a single shot and for larger systems such as engines which are divided into segments with specific P(k/h) values for each segment.

3. Fault Tree Analysis (FTA)

As previously mentioned, the Fault Tree Analysis is not required by MILSTD 2069 as a task in a survivability assessment. It is another method used to identify critical components. It usually conducted when there has been no FTA provided for the system under analysis. It can actually replace the FMEA and is done in parallel to the DMEA.

Ball [Ref. 2:p. 149] calls this analysis the "top down" approach. An undesirable event is the catalyst for the Fault Tree Analysis, then the events or combination of events that caused the undesirable event are determined. The undesirable event for this case study is the A-level attrition kill. The contractor will analyze what could cause this event to occur; breaking down systems into their components and examining them for levels of redundancy, if any. As seen from Figure 3.8 [Ref. 2:p. 149], logic

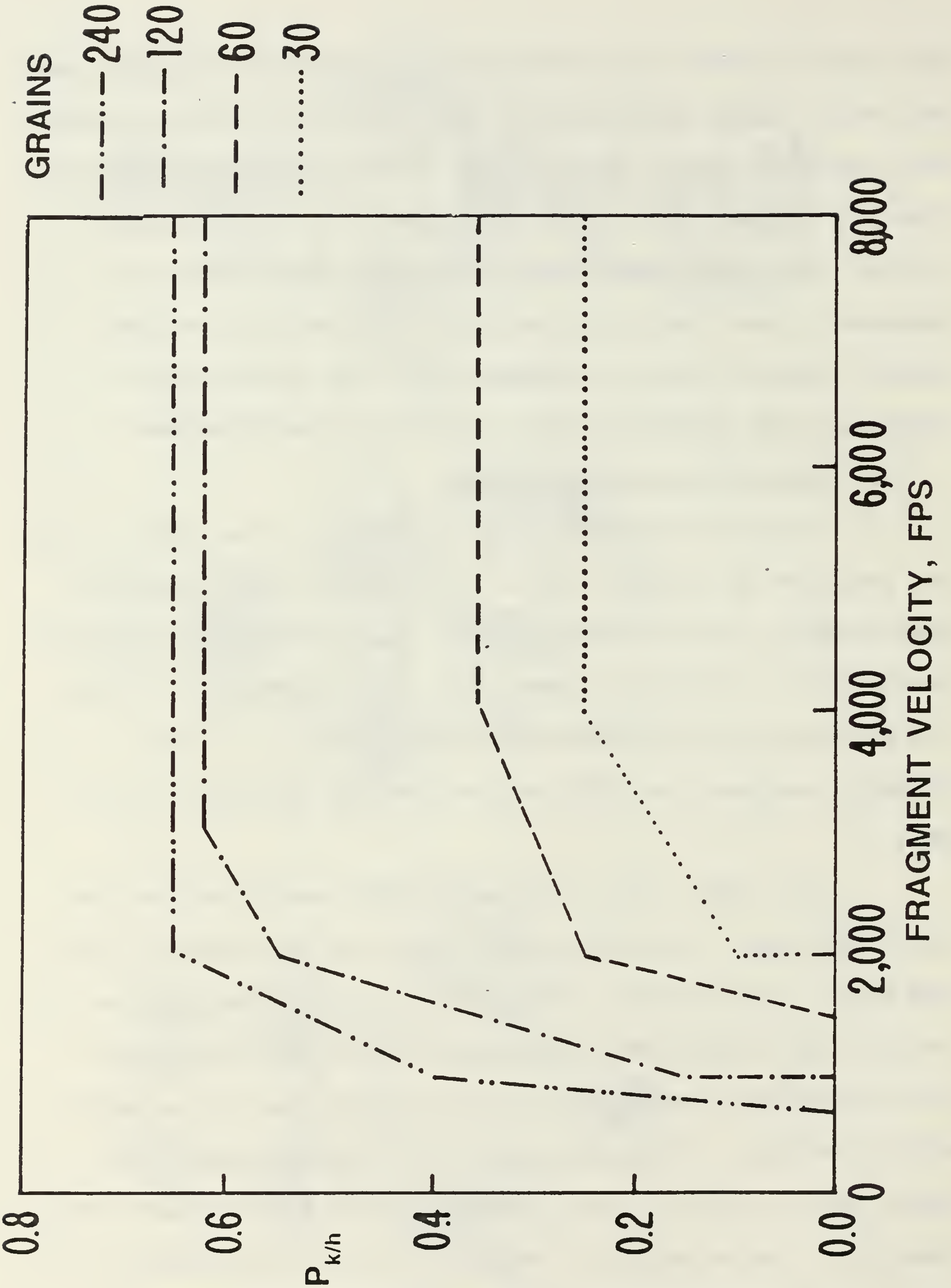


Figure 3.7 Example P(k/h) Function

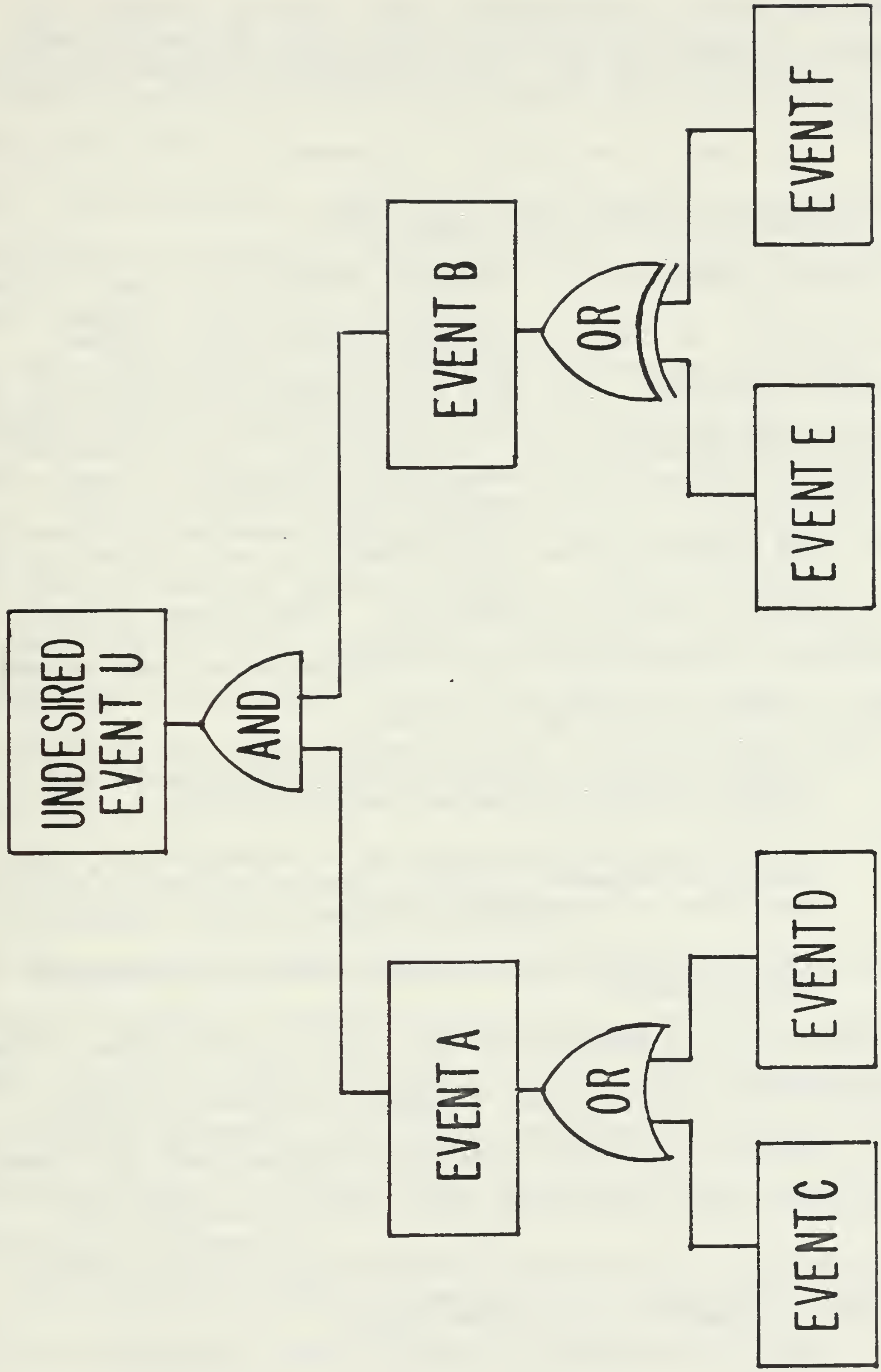


Figure 3.8 Generic Fault Tree Diagram

symbology helps to branch the fault tree by recognizing component redundancy and the relationship between cause and effect.

E. AIRCRAFT VULNERABILITY ASSESSMENT

From a contractor's viewpoint, MILSTD 2069 [Ref. 1] is very specific in its requirements concerning a vulnerability assessment. The data and information discussed in the previous paragraphs is the backbone of any vulnerability assessment. In the conceptual/preliminary design phase, the contractor has the freedom to use either his own or government approved methodology. Regardless of the methodology, it must meet the following objectives as set forth by MILSTD 2069 [Ref. 1:p. 21].

(1) Identify deficiencies and evaluate methods and design changes to reduce vulnerability.

(2) Provide quantified measures of vulnerability for specific threats and kill levels for use in design analyses and trade-off studies.

(3) Provide inputs for the survivability assessment of the aircraft.

Vulnerability assessments can take various forms. The contractor may use detailed computer analyses with geometric models and various computer programs such as those mentioned by Ball [Ref. 2:pp. 192-198]. Because this aircraft is in the conceptual design phase, this method will not be used for this case study.

The contractor must also do a detailed analysis for the aircraft's single hit vulnerable area using the P(k/h) functions for the components. According to Ball [Ref. 2:p. 154], the vulnerable area is "a theoretical non-unique area presented to the threat, that if hit by a damage mechanism, would result in an aircraft kill.

The contractor may be required to develop a vulnerability analysis based on the P(k/d), the "probability of kill given a detonation envelope" if the weapons system is expected to encounter HE warheads in its mission profile.

Another area of vulnerability study is the laser threat. The P(l/o), " probability of kill given a specific laser power lock-on for a specified period of time. This is becoming extremely important with current technology development.

F. AIRCRAFT SUSCEPTIBILITY ASSESSMENT

The contractor must utilize the results of the Mission Threat Analysis to conduct a proper susceptibility assessment. Since the susceptibility of an aircraft depends upon the mission scenario, the threat encountered, and the aircraft itself, a complete and thorough Mission Threat Analysis is essential.

The contractor makes judgements and assessments based on the conceptual design, known or proposed tactics, aircraft designed performance, the characteristics of the

threat, its lethality, and the environment to assess how well an aircraft can avoid being damaged while performing its assigned mission. Or it can be stated that the contractor uses all weapons, aircraft, and environmental data to determine the net probability the aircraft is hit by the damage mechanism.

There are several specific weapons and aircraft parameters that the contractor must consider when performing this assessment.

(1) The threat parameters include:
-detection
-acquisition
-lock on
-track
-missile guidance
-gun fire control
-command and control interfaces

(2) The aircraft parameters include:
-detectable signatures (IR, RCS, aural)
-counter measures
-tactics
-flight path and performance

The contractor must make trade-off studies, especially in the conceptual design phase, during a susceptibility assessment. For example, industry must weigh the advantages/penalties in weight and cost replacing conventional nozzles with 2-D nozzles to reduce the IR signature of an exhaust system. Or, adding a more powerful jammer based on the perceived threat, and fighting with the weight, cost and size parameters inherent in such a decision. There are many analytical processes involved in this type of

analysis; the contractor must document each analysis and produce the most efficient solution to the aircraft's susceptibility.

G. AIRCRAFT SURVIVABILITY ASSESSMENT

The Survivability Assesment is the capstone of the survivability program. It is the culmination of a quantitative measure of the aircraft's survivability. The contractor must combine the results of all of the above mentioned assessments and determine the effectiveness of the weapons system it has designed. Specifically, the contractor is required by MILSTD 2069 [Ref. 1:p. 23] to complete an assessment using:

(1) The results of the mission threat analysis.

(2) The results of the vulnerability analysis.

(3) The results of the susceptibility analysis.

The assessment should address the following categories:

(1) Laser availability if DOD specifies the need.

(2) System cost effective analysis. This should be done as trade-off studies to determine the point where making the plane survivable is no longer cost effective. A measure of effectiveness is required for comparison purposes. This will show the relative effectiveness of a system with its inherent costs. In the conceptual design phase, this is limited by the stage of system development.

(3) Survivability enhancement trade-off studies. The contractor is responsible to provide an in depth analysis to DOD identifying the effects, benefits and penalties in survivability enhancement parameters. A trade-off study shall describe the survivability enhancement techniques considered;

and how vulnerability and susceptibility reduction was realized by the use of these techniques. Coincident with this should be an assessment on the aircraft's performance, weight, cost, reliability, etc., if such an enhancement were incorporated.

The contractor's development of a survivability assessment is critical to the design of the aircraft. The conceptual/preliminary phase, with its degree of freedom, makes it an excellent phase to assess a system, from both cost effective and performance points of view.

H. COMBAT DAMAGE REPAIR ASSESSMENT

The contractor must design a repairable system. For a survivability program, the contractor estimates the manhours, costs, logistics and repair levels of the aircraft in a combat environment. In the conceptual/preliminary design phase, the contractor must highlight design items for quick turn-around fixes; i.e., those he feels are inherent in the design of the system. He must, if able, identify and describe complete repairs and proposed levels for major repair systems. Finally, he must identify those spare parts which would require a long lead time in procurement; and the amount of parts stocking required for a combat environment.

MILSTD 2069 [Ref. 1] concludes its documentation of the groundwork for survivability program by briefly discussing the required survivability enhancement features that are to be considered in a design. These are too numerous to

discuss individually. The conceptual design phase requires that enhancement features be the basis for trade-off studies. The design survivability enhancement features will discussed in the case study in the FMECA, then engineering analysis will be used to recommend improvements in the design including incorporation of applicable enhancement features listed in MILSTD 2069 [Ref. 1:pp. 25-35].

The following chapters encompass the case study itself. The next chapter defines the design of the aircraft used in the assessment.

IV. THE AIRCRAFT

The aircraft used for this case study is the result of a course the author took at NPS. An RFP was developed by Professor R.D. Zucker to be used as the basis for the design. It is a generic, unclassified RFP, having no known connection to any existing or proposed weapons system. The RFP was presented as follows.

A. REQUEST FOR PROPOSAL

-TYPE:	Light/medium weight attack aircraft, land or carrier based.
-CREW:	1 (single seat)
-MINIMUM PAYLOAD:	4 cruise missiles (1200 lbs. each) 4 sidewinder missiles (190 lbs. each)
-PROPULSION SYSTEM:	generic "rubber engine" capable of producing 20,000 lbs. thrust at sea level.
-DESIGN SPEED:	Mach 1.1 (dash speed-total mission may be subsonic).
-TAKE-OFF DISTANCE:	3000 ft. (from land)
-LANDING DISTANCE:	3500 ft. (to land)
-PRIMARY MISSION:	Low level ordnance delivery from either carrier or land base, with full payload and no external fuel. (See V. Mission Threat Analysis)
-ALTERNATE MISSION:	High level ordnance delivery from either carrier or land base, with full payload and no external fuel. (See V. Mission Threat Analysis)

-MANEUVERABILITY:	Design load factor--8 g's. Sustained turn rate at P(s) = 0 is 4 g's at Mach 0.8 and 30,000 ft. Instantaneous turn rate at 8 g's is 16 degrees per second at the "corner speed and 30,000 ft.

From this RFP and course material, the conceptual design of the A-20 ELIMINATOR was created (See Figures 4.1 and 4.2). Because the purpose of this case study is to assess the vulnerability of the aircraft in the conceptual/ preliminary design stage, the majority of work involved in creating the response to the RFP has been omitted. This response, which was supposed to represent a defense contractor's submission of a proposed design, required 175 pages to complete. For this reason, a summary of design and performance specifications for the ELIMINATOR follows.

B. DESIGN SUMMARY

Total Airplane

Overall length	48.23 ft
Overall height	15.20 ft

Wing

Area (S)	415.4 ft
Span (b)	38.129 ft
Aspect Ratio (AR)	3.5
Chords	
Root Chord	17.43 ft
Tip Chord	4.4 ft
MAC	12.2 ft
y-MAC	7.6 ft
L.E. Sweep	41.5 deg
c/4 Sweep	35.7 deg
Taper Ratio	0.25
t/c	7.5%

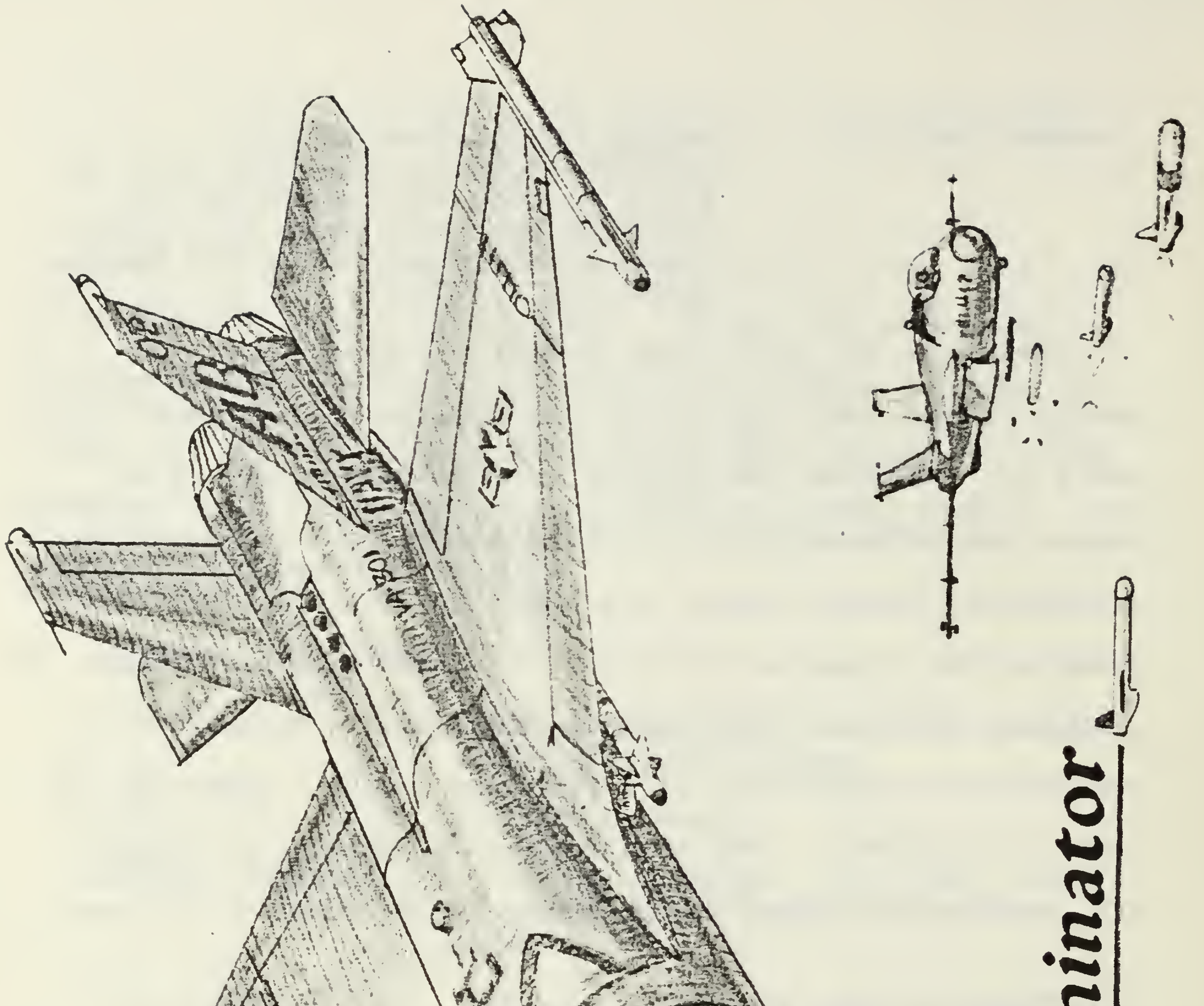


Figure 4.1 A-20 ELIMINATOR

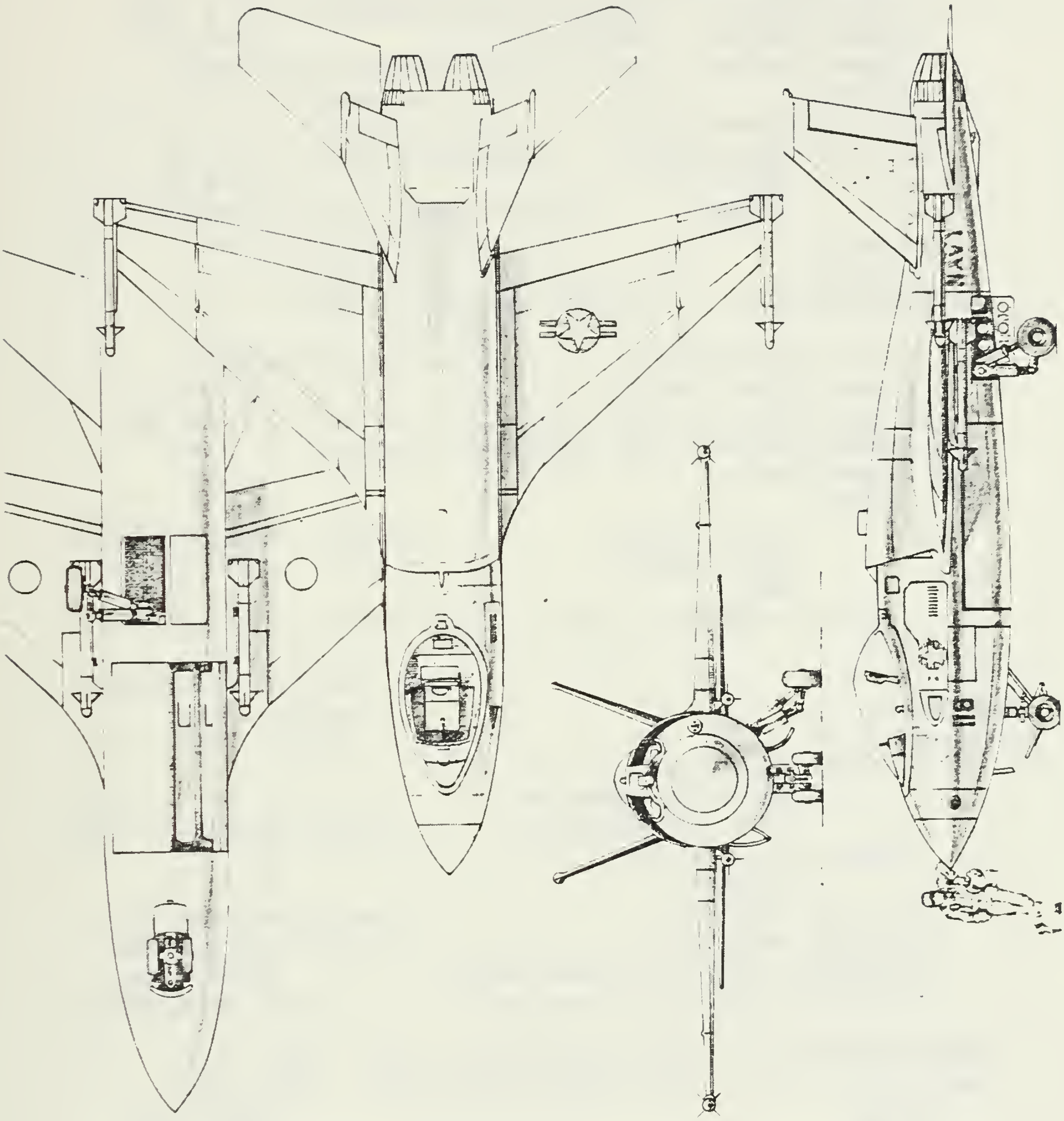


Figure 4.2 A-20 ELIMINATOR (four view)

Horizontal Tails

Tail Coefficient	0.4
Area (S per tail)	67.6 ft
L.E. Sweep	41.5 deg
Span (exposed per tail)	8.25 ft
Taper Ratio	0.48
Chords	
Root Chord	10.0 ft
Tip Chord	4.8 ft
MAC	7.78 ft
y-MAC	4.83 ft
t/c	7.5%

Vertical Tails

Tail Coefficient	0.6
Area (S per tail)	52.8 ft
L.E. Sweep	41,45 deg
Span (exposed per tail)	8.0 ft
Taper Ratio	0.342
Chords	
Root Chord	9.5 ft
Tip Chord	3.25 ft
MAC	6.88 ft
y-MAC	3.97 ft
t/c	7.5%

Engines

Thrust-to-Weight	
with afterburner	1.04
w/o afterburner	0.61
Number of Engines	2
length	11.0 ft
diameter	2.4 ft
weight	1450.0 lbs
Maximum Thrust at Sea Level	38600 lbf
Capture Area (per engine)	1.68 sq ft

Aircraft Weight

W(o)	37327 lb
W(e)	18089 lb
W(f)	10800 lb

Landing Gear

Main Landing Gear (single tire)	
Diameter	28.7 in
Width	8.6 in
Wheel Diameter	13.4 in

Main Landing Gear Shock	
Stroke	25 in
Strut Diameter	4.1 in
Minimum Shock Length	5.2 ft
Nose Landing Gear(dual tire)	
Diameter	21.5 in
Width	6.8 in
Wheel Diameter	10.1 in
Nose Landing Gear Shock	
Stroke	24.2 in
Strut Diameter	2.0 in
Minimum Shock Length	5.04 ft
Balance Parameters	
Static Tail Down Angle	15.0 deg
Turnover Angle	53.97 deg

-AERODYNAMICS SUMMARY

Design Lift Coefficient (Mach 0.87)	0.254
Maneuvering Devices	
L.E. Flaps	0-34 deg defl
T.E. Flaps	0-17 deg defl

-PERFORMANCE SUMMARY

Take-off distance	1706 ft
Landing distance	3535 ft
Maximum Speed	
Sea level with AB/without AB	1.04M/0.8M
30000 ft with AB/without AB	1.1M/0.9M

For the purpose of this case study, the author went beyond the purely conceptual design arena into some preliminary design work; creating and sizing the aircraft's subsystems, such as the hydraulics, flight controls, propulsion, etc. This was done to ensure a realistic

component base for the case study. This design work was based on existing systems in the inventory and current developments and technology in aircraft design.

It was not the author's intent to design the most survivable aircraft possible. The A-20 was designed to be representative of current technology. The survivability features inherent in the design will only lead to a better understanding of the methodology used in the assessment.

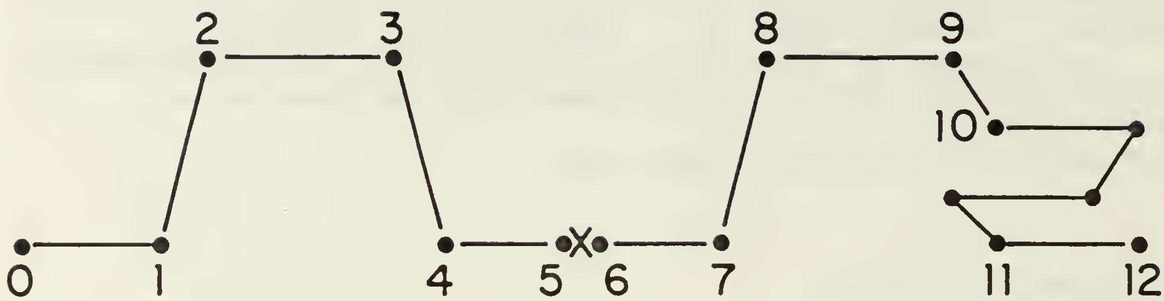
V. A-20 MISSION THREAT ANALYSIS

The Mission Threat Analysis is the first step in an aircraft survivability assessment. Background on the methodology for the Mission Threat Analysis is found in Chapter 3 of Ball [Ref. 2]. Specifically, Section 3.7 (pages 115-116) presents the steps Ball delineates as necessary for a proper assessment.

A. MISSION ANALYSIS

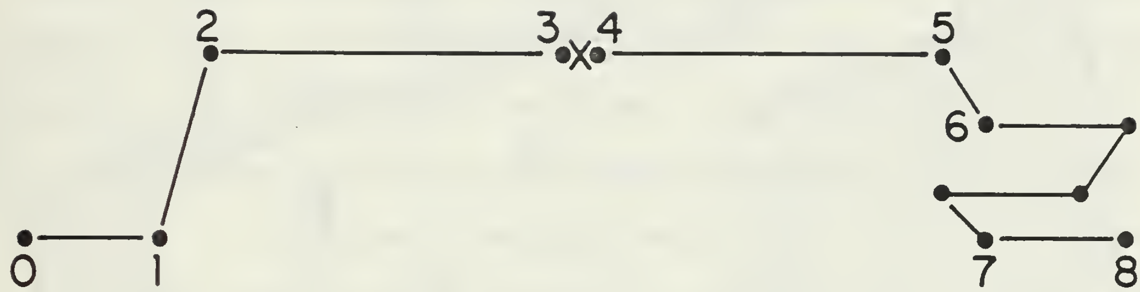
The Mission Analysis for an aircraft in the conceptual/preliminary design phase is driven by the RFP. For the A-20, the RFP requires the primary mission to be a high-low/low-high mission with speeds and altitudes depicted generically in Figure 5.1. The ordnance load is dependent upon target selection and intelligence. The alternate mission is stated in the RFP as a high-high/high-high mission profile as depicted generically in Figure 5.2. Again the ordnance load is dependent upon target selection and intelligence.

From the design standpoint, the A-20 is a multi-mission attack aircraft. It is designed to deliver ordnance on a designated target in a variety of roles that fit both the primary and alternate mission descriptions such as close



0-1 Taxi and take-off
1-2 Climb to 30,000 ft. cruise altitude
2-3 Cruise at 0.75 Mach for 250 NM to ingress area
3-4 Descend to ingress point (sea level)
4-5 Ingress 50 NM at 0.9 Mach to target area
5-6 Low altitude ordnance delivery on target
6-7 Fly 50 NM to egress point at 0.9 Mach
7-8 Climb to 30,000 ft. cruise altitude
8-9 Cruise at 0.8 Mach for 250 NM to descent point
9-10 Descend to loiter altitude
10-11 Loiter at 0.27 Mach at sea level for 20 minutes
11-12 Approach, land and taxi to ramp

Figure 5.1 Generic High-Low/Low-High Mission



0-1 Taxi and take-off
1-2 Climb to 30,000 ft. cruise altitude
2-3 Cruise at 0.75 Mach for 353 NM to target area
3-4 High altitude ordnance delivery on target
4-5 Cruise at 0.8 Mach for 353 NM to descent point
5-6 Descend to loiter altitude
6-7 Loiter at 0.27 Mach, at sea level for 20 minutes
7-8 Approach, land and taxi to ramp

Figure 5.2 Generic High-High/High-High Mission

air support/tactical interdiction, surface combatant destruction, armed reconnaissance and defense suppression.

Of the missions mentioned, the close air support/ tactical interdiction mission was selected for case study evaluation. This mission requires the aircraft to be exposed to surface and air threats from either sea or land based systems. The RFP requires an assessment from both sea and land based operating theaters. The spectrum of threats that the A-20 could be exposed to covers the majority of the Soviet naval and cities defense inventory.

Specific missions as conceived by the author can be seen in Figures 5.3 and 5.4. The aircraft can be deployed from either sea or land based assets and can fly the mission profile as depicted to either high or low level ordnance delivery, depending upon mission requirements. This case study will examine the threats expected in the low level scenario.

The A-20 leaves it base of operations (either carrier for USN or land for USAF) and proceeds to fly the high-low/low-high mission. Figure 5.3 shows the combat radius to be approximately 300 NM. This mission assumes no external tanks or in-flight refueling.

The tactics conceived for an attack mission of this type are those which are characteristic of attack aircraft currently in the US inventory. Depending on the ordnance to be delivered, these tactics could encompass a low

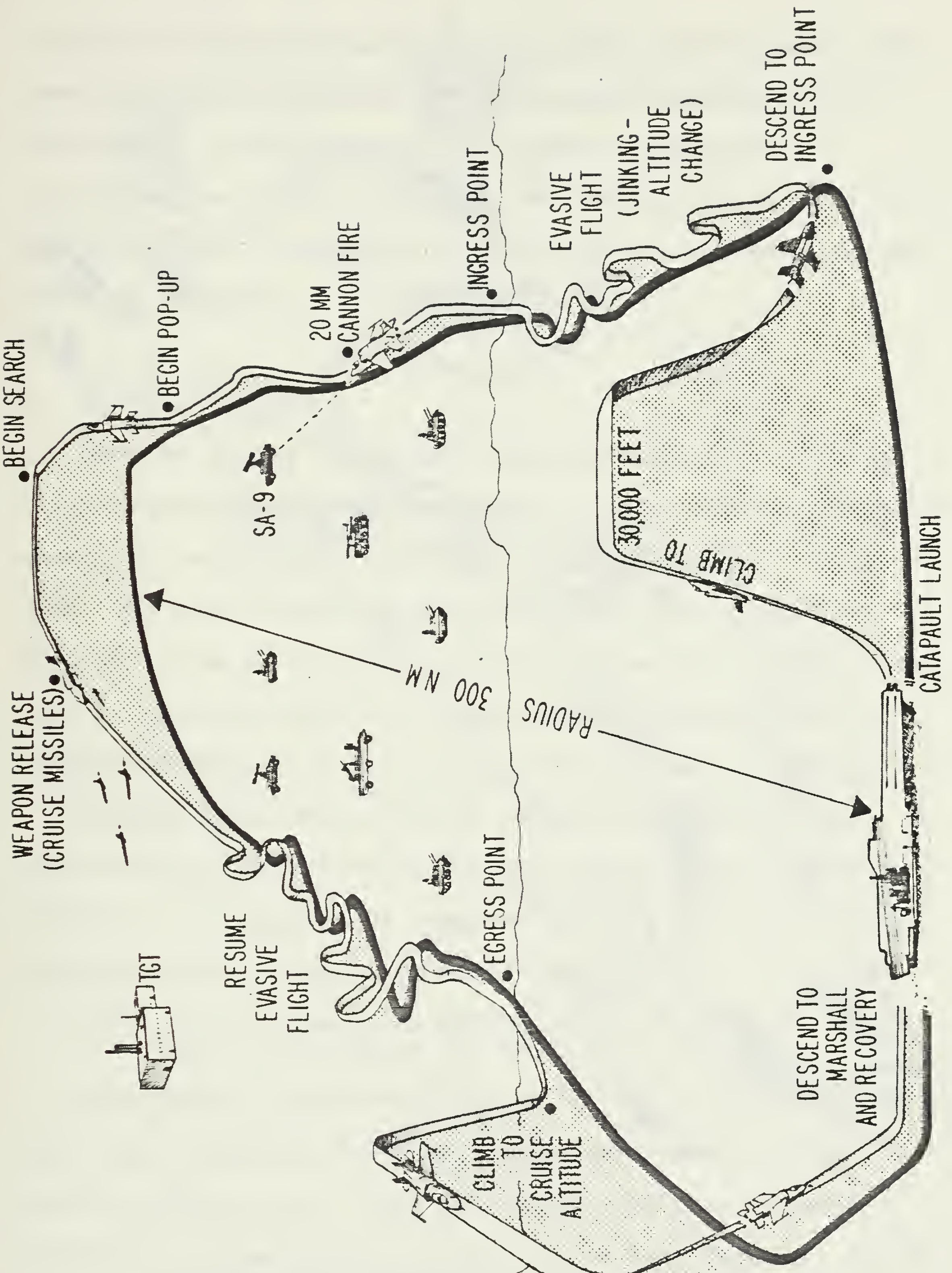


Figure 5.3 A-20 High-Low/Low-High Mission

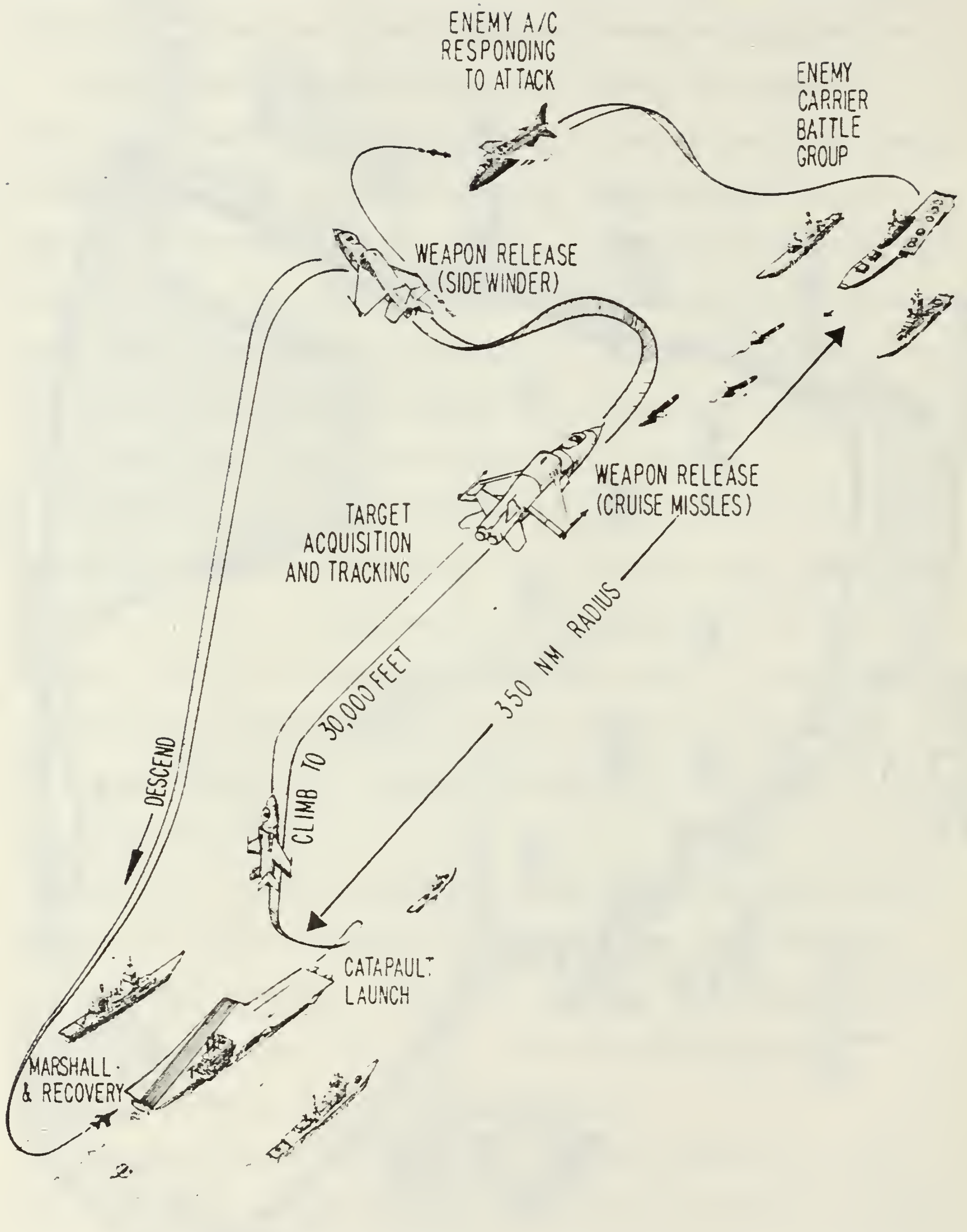


Figure 5.4 A-20 High-High/High-High Mission

altitude evasive ingress and pop-up ordnance delivery (for bombs and cruise missiles stored in the weapons bay--see Figure 5.5), a straight-in high speed strafing run (utilizing the 20 mm cannon), or a jinking-maneuvering air-to-air scenario utilizing the sidewinders (situated on the external stations).

B. THREAT ANALYSIS

Because of the conceived design versatility of the A-20, the threats it could encounter in a hostile environment encompass the majority of Soviet SAM/AAA arsenal. Over land, the A-20 could encounter anything from a ZSU-23-4 "Shilka" to an SA-7 or SA-9 site. At sea the threats are just as numerous; the A-20 could anticipate encounter conditions with 76 mm AAA or any one of the SAN systems.

Because this case study is using the close air support/tactical interdiction mission for an analysis, the threat to be assessed is narrowed down to the following representative, generic, system:

(1) SA-X, a generic IR homing missile. The fragment size is 100 grains for analysis.

This threat was chosen because of its utility against low level targets and its strategic importance to the Soviet defense plan. This assessment will determine the single hit vulnerability values of the A-20 for this threat propagator based on engineering evaluations of the

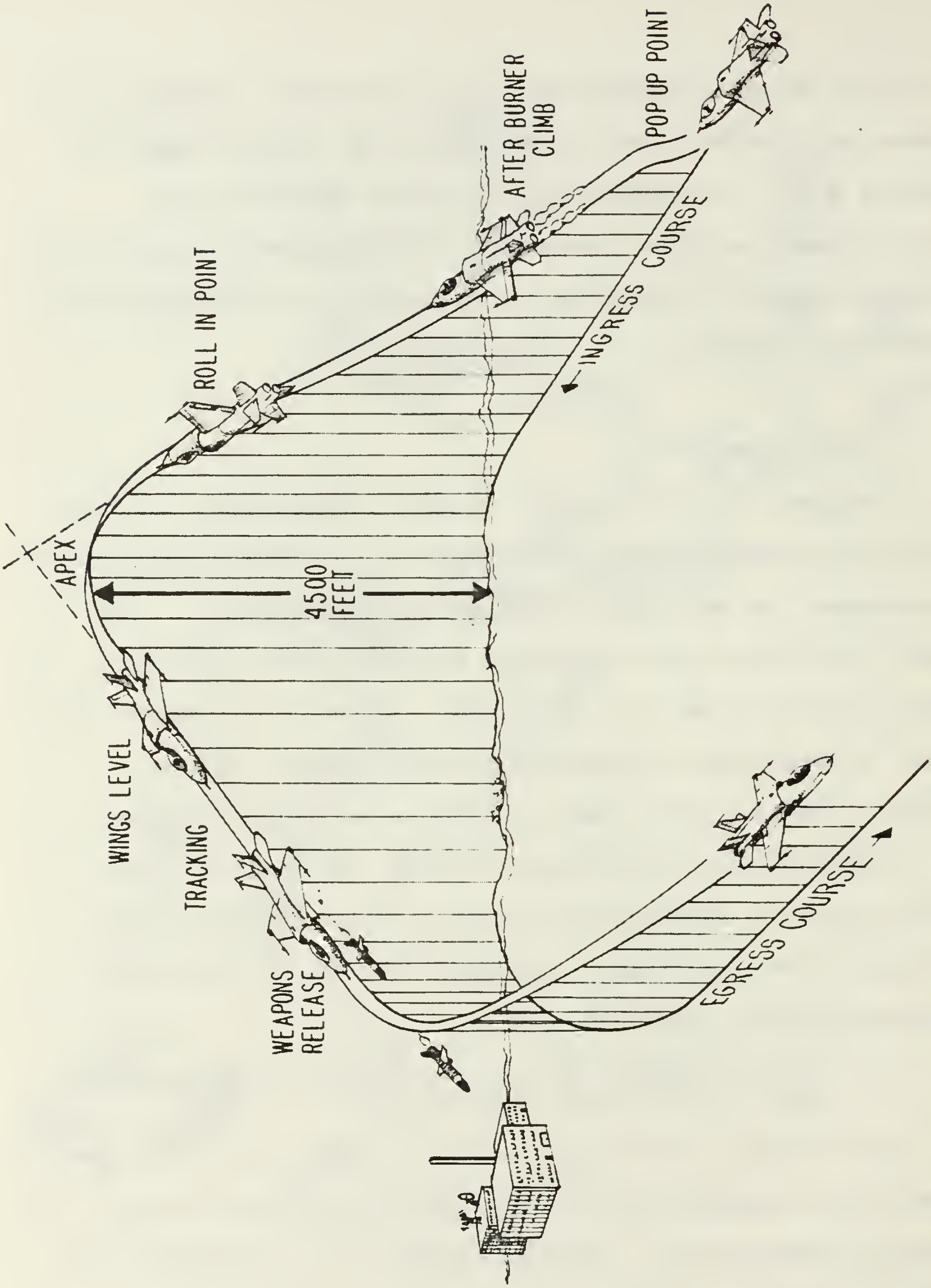


Figure 5.5 A-20 Conceptual Tactics

conceptual/preliminary design. Specifically, the component and aircraft probabilities of kill given a hit, the component and aircraft probabilities of survival given a hit, and the component and aircraft vulnerable areas.

VI. A-20 FLIGHT AND MISSION ESSENTIAL FUNCTIONS

The methodology for this task is found in both Chapter 2 and Chapter 5 of Ball [Ref. 2]. In Chapter 2, pages 39-60, Ball discusses a tactical aircraft and its systems in detail to help the reader learn the major components and their importance. In Chapter 5, pages 138-140, Ball presents the methodology to conduct the Flight and Mission Essential Function portion of the analysis.

Flight and Mission Essential Functions are those functions that must be properly performed in order for the aircraft to complete its mission. These functions are also known as "critical" functions. They are functions that must be performed by each of the aircraft's systems, sub-systems and components to meet the survival requirements of each applicable kill category; either conventional attrition or mission abort. The kill category selected for this case study is the attrition kill. The attrition kill is a measure of the degree of aircraft damage which renders it incapable of continued conventional flight. This results in a crash with damage beyond that of economic repair, and a loss of the aircraft from the inventory. The level of attrition kill selected for analysis is the "5 minute A-level kill" as described by Ball [Ref. 2:p. 136].

Required mission functions are those necessary to conduct the missions determined by the Mission Threat Analysis in the previous chapter. These missions can be divided into separate and distinct phases in order to determine which subsystem contributes to a mission essential function, a flight essential function (such as Lift, Thrust or Control), or both. There are several phases common to all the missions discussed. They are:

(1) mission planning
(2) man up/take off
(3) rendezvous, climb to cruise altitude
(4) fly tactical profile
(5) rendezvous, climb to cruise altitude
(6) descend to marshall/begin approach
(7) carrier arrestment/land

From the case study standpoint, the most critical phase of the analysis is phase four, the tactical profile phase. The aircraft must be able to fly and perform its designed tactical mission of delivering ordnance during this phase. Since the methodology is the same for all seven phases, only that involving phase four will be demonstrated. Phase four may be further broken down into subphases to determine subsystem contributions.

(4) Fly Tactical Profile
---subphases---
-descend to ingress point
-descend to tactical low level altitude, commence evasive flight profile
-search and acquire target
-perform tactical weapons delivery maneuver
-weapons release
-resume evasive flight profile to egress point

For case study purposes, the aircraft is composed of a number of systems that can be broken down into various subsystems that affect its ability to fly in a controlled flight environment and to conduct and complete its mission [Ref. 2:pp. 39-60]. Table 6.1 shows the aircraft broken down into various systems and subsystems with the functions of each listed.

Using the subphases determined from the mission profile phase and the systems and subsystems (and their functions) as noted in Table 6.1, a table or matrix is developed to show which systems are required during each subphase of the tactical profile. Table 6.2 is a summary of the final analysis of the Mission and Flight Essential Functions for the tactical profile phase of the overall mission. For this table, each function of the system and subsystem was evaluated to determine its participation in the success of the overall phase. As can be seen, some systems and subsystems contribute to both the flight and mission success of the phase; while others, such as the avionics, contribute to only the mission portion of the tactical profile phase.

This method of analysis is done for each one of the mission phases. This analysis of which systems and subsystems provide the essential functions is the first step in determining each system's and subsystem's critical components. Now that this chapter has presented the

TABLE 6.1 SYSTEMS/SUBSYSTEMS AND FUNCTIONS

System/Subsystem	Function
Pilot	Maintain aircraft control
Engines Compressors Combustors Turbines Fuel Controls Hydraulics Oil Systems Electrical Systems Mounts	Provide and/or maintain required thrust
Accessory Drives	Provide power for accessories
Throttle Control Subsystem	Provide control of engine power output.
Mechanical Flight Controls Longitudinal Linkages Lateral Linkages Control Stick	Provide complete mechanical back-up control in case of Automatic Flight Controls failure. Provide pilot input to control surfaces.
Automatic Flight Controls Flight Control Computers Flight Control Surfaces Rate Sensors Air Data Sensors Stick Force Sensors Accelerometers Rudder Pedal Transducers Direct Electrical Link	Provide electrical signals to all flight control surfaces.
Electrical System	Provide electrical power during all flight phases.
Fuel System Tanks Lines Pumps	Store and deliver fuel to engines.

TABLE 6.1 (cont.) SYSTEMS/SUBSYSTEMS AND FUNCTIONS

System/Subsystem	Function
Hydraulic Subsystems Reservoirs Accumulators Lines Pumps Manifolds Filters and Coolers Primary Actuators	Provide hydraulic power from at least one system to move primary control surfaces, weapons bay door actuators, cannon, landing gear, etc..
Structures Control Surface and Wing Attach Fittings Spar Caps Control Surface and Wing Attach Points	Carry structural loads and provide for structural integrity of the aircraft.
Air Conditioning Subsystem	Provide required air conditioning for selected components.
Airborne Weapons Control Components	Provide airborne weapons control and monitoring.
Communication and Identification Components	Provide communication and identification.
Electronic Warfare Components	Provide ECM capabilities.
TACAN	Provide navigation capability
Mission Computers	Provide data processing capability.
Instrument Panels	Provide pilot monitoring and control of subsystems.
Displays Radar	Display information
Air Data Equipment	Acquire, process and display air speed and angle-of-attack information.

TABLE 6.2

TACTICAL PROFILE PHASE--FLIGHT AND MISSION ESSENTIAL FUNCTION SUMMARY

m = mission flt = flight b/u = backup

	Tactical Profile Subphases					
System/Subsystem	Descend to Ingress Point	Descend, Commence Evasive Profile	Search and Acquire Target	Perform Delivery Manuever	Weapon Release	Evasive Flight to Egress
Pilot	m\flt	m\flt	m\flt	m\flt	m\flt	m\flt
Accessory Drives	flt	flt	----	----	----	flt
Mechanical Flight Controls	flt (b/u)	flt (b/u)	----	flt (b/u)	----	flt (b/u)
Electronic Flight Controls	flt	flt	----	m\flt	m\flt	flt
Flight Control Electrical Power System	flt	flt	----	m\flt	m\flt	flt
Fuel System	m\flt	m\flt	----	m\flt	----	m\flt
Throttle Control System	flt	flt	----	flt	----	flt
Hydraulic Systems	flt	flt	----	m\flt	m\flt	flt
Structures	flt	flt	----	m\flt	----	flt
Air Conditioning System	----	----	m	----	m	----

TABLE 6.2 (cont.)
TACTICAL PROFILE PHASE — FLIGHT AND MISSION ESSENTIAL FUNCTION SUMMARY

m = mission flt = flight b/u = backup

System/Subsystem	Tactical Profile Subphases: Descend to Ingress Point	Descend, Commence Evasive Profile	Search and Acquire Target	Perform Delivery Maneuver	Weapon Release	Evasive Flight to Egress
Airborne Weapons Control Components	----	----	----	----	m	----
Communication/Identification Components	m	----	----	----	----	m
Electronic Warfare Components	m	m	----	----	----	m
Engines	flt	m\flt	----	m\flt	----	m\flt
TACAN	----	----	----	----	----	----
Mission Computers	----	----	m	m	m	----
Instrument Panels	flt	flt	m	m\flt	m	flt
Displays	flt	m\flt	m	m	m	flt
Air Data Equipment	m\flt	m\flt	m\flt	m\flt	m	m\flt

flight and mission essential functions methodology of the A-20, the next chapter will provide the Failure Mode, Effects and Criticality Analysis (FMECA) for the aircraft.

VII. A-20 FAILURE MODE, EFFECTS, AND CRITICALITY ANALYSIS

The methodology for the Failure Mode, Effects, and Criticality Analysis (FMECA) is presented by Ball [Ref. 2] in Chapter Five. The FMECA is broken down into two parts, a Failure Modes and Effects Analysis (FMEA) and a Damage Modes and Effects Analysis (DMEA). Also included in this section (but not actually part of the FMECA as required by MILSTD 2069), is a Fault Tree Analysis (FTA). The FTA is an alternate, and very effective, approach to identifying the critical components of a system. Each of these tasks will be applied to the aircraft using the methodology found on pages 138-153 of Ball [Ref. 2].

A. A-20 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

When a survivability analysis is conducted on a design, the FMEA is normally provided by engineers who are concerned with system safety, reliability and maintainability. It is based on design requirements, historical data (if the system is still in concept stage), predicted performance measurements and sound engineering judgement. This analysis is not concerned with the cause, but with the effect. The FMEA for this case study is presented in two parts: (1) the systems descriptions and (2) the results of the analysis in tabular format.

The major input to the FMEA is the physical and functional description of the aircraft and its subsystems and the data obtained from the Flight and Mission Essential Functions Analysis. For an aircraft in the conceptual/preliminary design phase, this consists of conceptual drawings and narrative descriptions of what the designer thinks the aircraft should look like and be capable of.

The FMEA is usually a single component failure analysis. It is a procedure that does not look at the cause of failure, but at the component failure itself and its effect upon the system; i.e., can it (the subsystem and system) still perform its essential functions with this component damaged. In other words, how does the failure of the component affect the subsystems operating ability; which in turn affects the systems operating ability.

The FMEA for this case study is presented below in two parts: (1) the systems descriptions and (2) the results of the analysis in tabular format.

1. Systems Descriptions

Conceptual drawings (see Figures 7.1 through 7.6) and a brief description of the Fuel, Hydraulics, Flight Controls, Propulsion, Armament and Structural Systems of the case study aircraft follows. These subsystems were chosen for analysis because they are the major subsystems of the aircraft and are well developed in the conceptual/ preliminary design phase. Also, each of these subsystems

has an affect on the ability of the aircraft to perform its essential functions in the tactical subphase (as determined in the Flight and Mission Essential Functions analysis).

a. The Fuel System

The A-20 fuel system consists of fuel storage and transfer tanks, plumbing, on board and in-flight fueling and refueling devices, and associated filters and pressurization system. As seen in Figure 7.1, there are six internal tanks: four fuselage tanks, and two integral wing tanks. In addition, there is a vent tank located in each vertical stabilizer. The A-20 also has the capability to carry a centerline mounted external fuselage tank.

The internal fuel system is designed to carry 10,400 pounds of fuel. The two fuselage tanks located longitudinally along either side of the weapons bay serve as transfer tanks. The integral wing tanks also serve as transfer tanks. The aft fuselage tank, located in the underside of the aircraft, is also a transfer tank, but can be switched to a feed tank for either engine if necessary. The forward fuselage tank is the primary feed to both of the engines with each engine having a separate feed line from this tank. This tank is non-transferable and carries the "get-home" fuel. The forward and aft tanks are both self sealing. All tanks have fire/explosion suppresion foam installed in the ullage. The vent tanks in the vertical tails are designed to collect fuel that happens to get

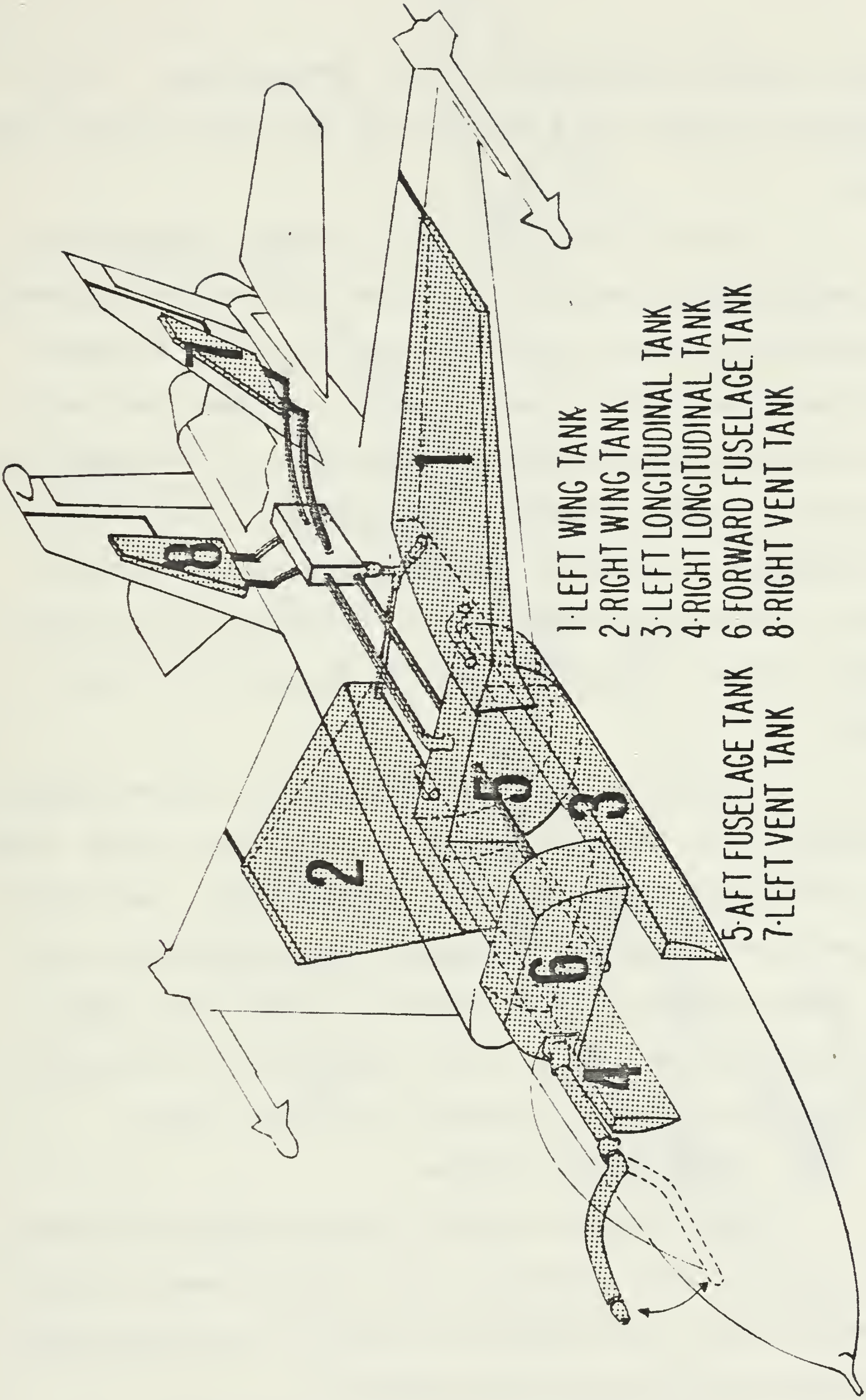


Figure 7.1 A-20 Fuel System

into the venting lines during high "g" maneuvers. It is collected in these tanks and gravity fed back into the fuel system.

As with most Navy fuel systems, fuel transfer is accomplished by motive flow, thus eliminating the need for electrical power to feed the engines. The transfer system can automatically sequence fuel to keep the feed tanks full for maximum engine performance; or the pilot can select fuel transfer manually under failure conditions. The automatic transfer is designed to take into account weapons release and burned fuel to maintain a relatively constant center of gravity location through all flight regimes.

As can be seen from Figure 7.1, the majority of the plumbing for the fuel system is within the tanks, helping to eliminate excess exposed surface area. The motive flow and boost pumps are driven off the accessories section. Boost and motive flow pumps are both three stage, single shaft pumps. These pumps operate by the venturi principle with regards to pressure and flow rates.

b. The Hydraulic System

The hydraulic system supplies hydraulic power to all flight control surfaces, the landing gear brakes, the cannon drive, the weapons bay doors, the landing gear mechanism, and the nose wheel steering.

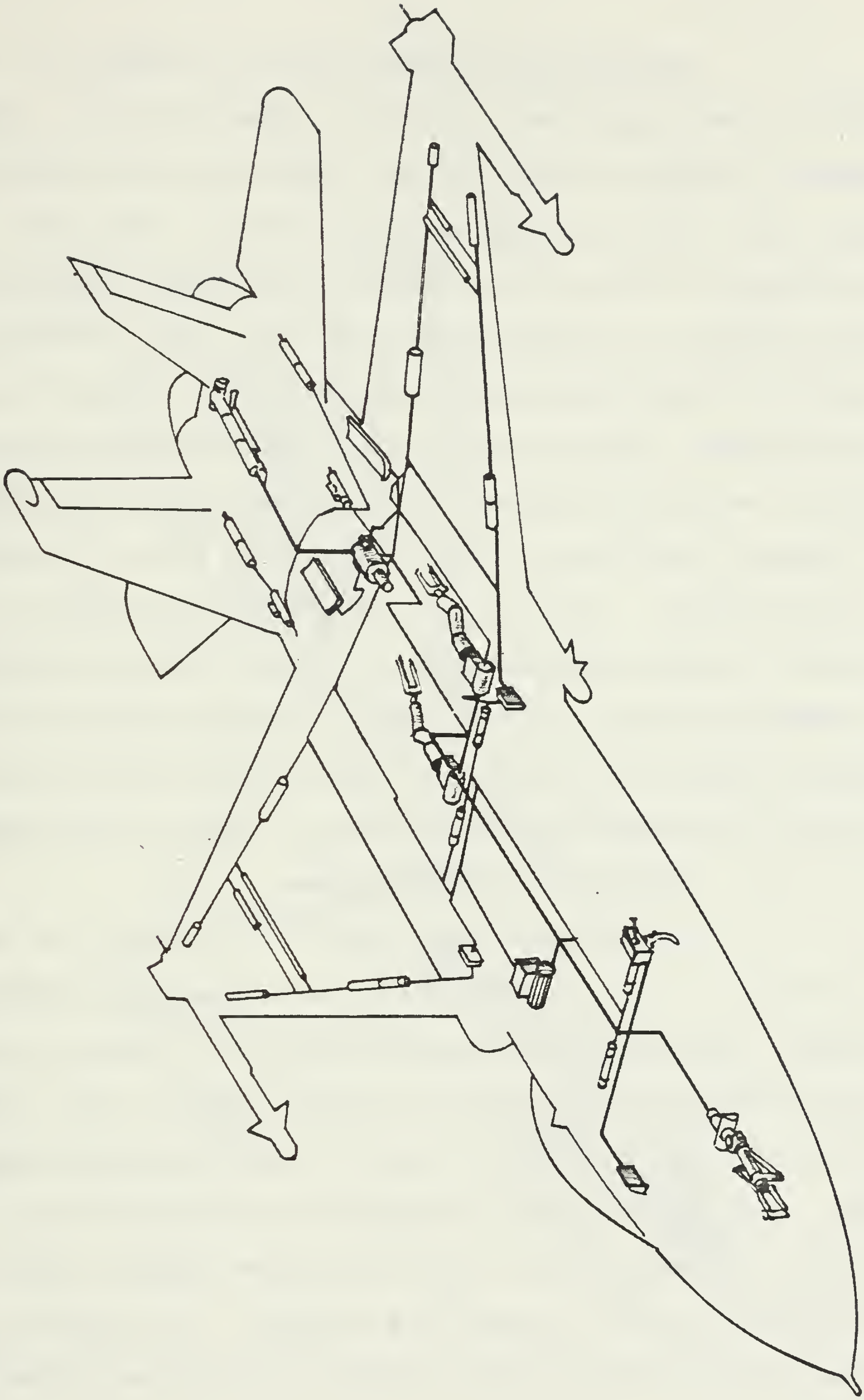


Figure 7.2 A-20 Hydraulics System

The hydraulic system, shown in Figure 7.2, consists of two independent hydraulic systems with two independent circuits in each system. There are three hydraulic reservoirs; one is always in backup for the other two. Each system is driven by an engine driven pump with electrical backup at a pressure of 3000 psi. Each system is capable of supplying hydraulic power to all flight control surfaces. The systems are monitored constantly by a control network for correct pressure and flow. The system can direct flow through one circuit while cutting off the flow in another. The control network can shut off one hydraulic system with automatic switching that is dependent on system pressure and flow rate. If the pressure in one system drops below 1200 psi., flow to this system is cut off and the backup reservoir comes on line to that system.

c. The Flight Control System

The flight control system of the A-20 is shown in Figure 7.3. It is actually three independent control systems, two electrical and one mechanical. There is an on board Automatic Flight Control System (AFCS), with a separate circuit for each one of the two flight control computers. The flight control computers are located in the forward electronics bay, just aft of the radome, and in the aft electronics bay, behind the cockpit. All control surfaces can be controlled by any one of the three systems.

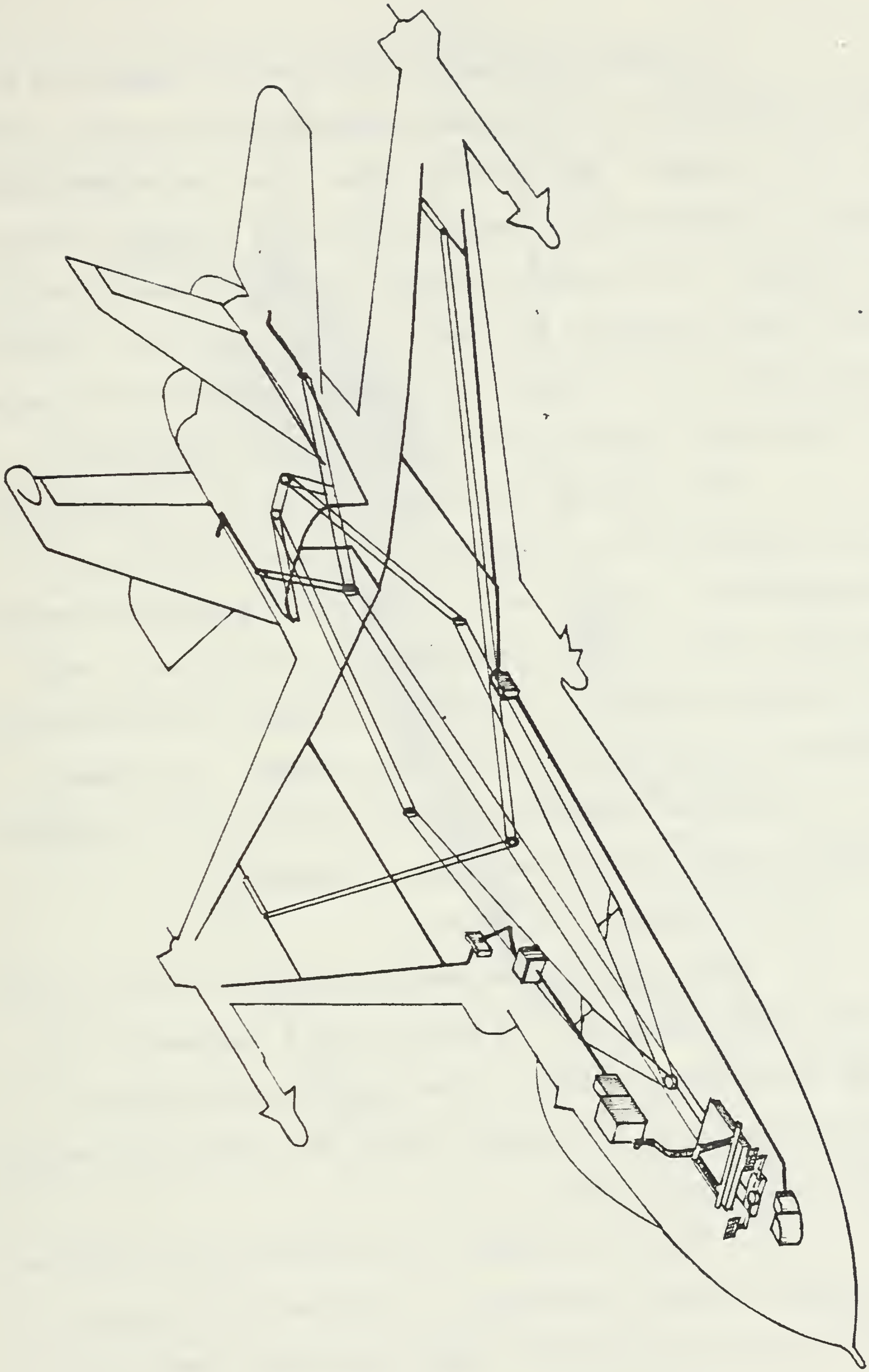


Figure 7.3 A-20 Flight Controls System

In normal operation, all control responses are due to electrical transmissions received from control stick and rudder inputs. At the same time stick and rudder pedal inputs are mechanically backed up through standard pulleys and linkages. All control surface movements come from hydraulic boost response to electrical or mechanical inputs. In the event of a hydraulic problem, the mechanical system can control the airplane without the boost system.

The aircraft is controlled in all three axis by the two flight control computers equipped with their own accelerometers, rate sensors, stick force and rudder pedal transducer inputs. Each computer has two channels, and each has the capacity to process all inputs and perform all necessary computations to fly the aircraft. In effect, there is multiple redundancy in the flight control system with both electrical and mechanical backups.

d. The Propulsion System

The propulsion system proposed for the A-20 is of 1990's technology. It is powered by a derivative of current development engines. The thrust capability of these engines is 20,000 pounds thrust per engine in maximum afterburner at sea level.

As shown in Figure 7.4, the propulsion system has a unique intake arrangement. Designed with survivability in mind, the intake wraps around the top of the

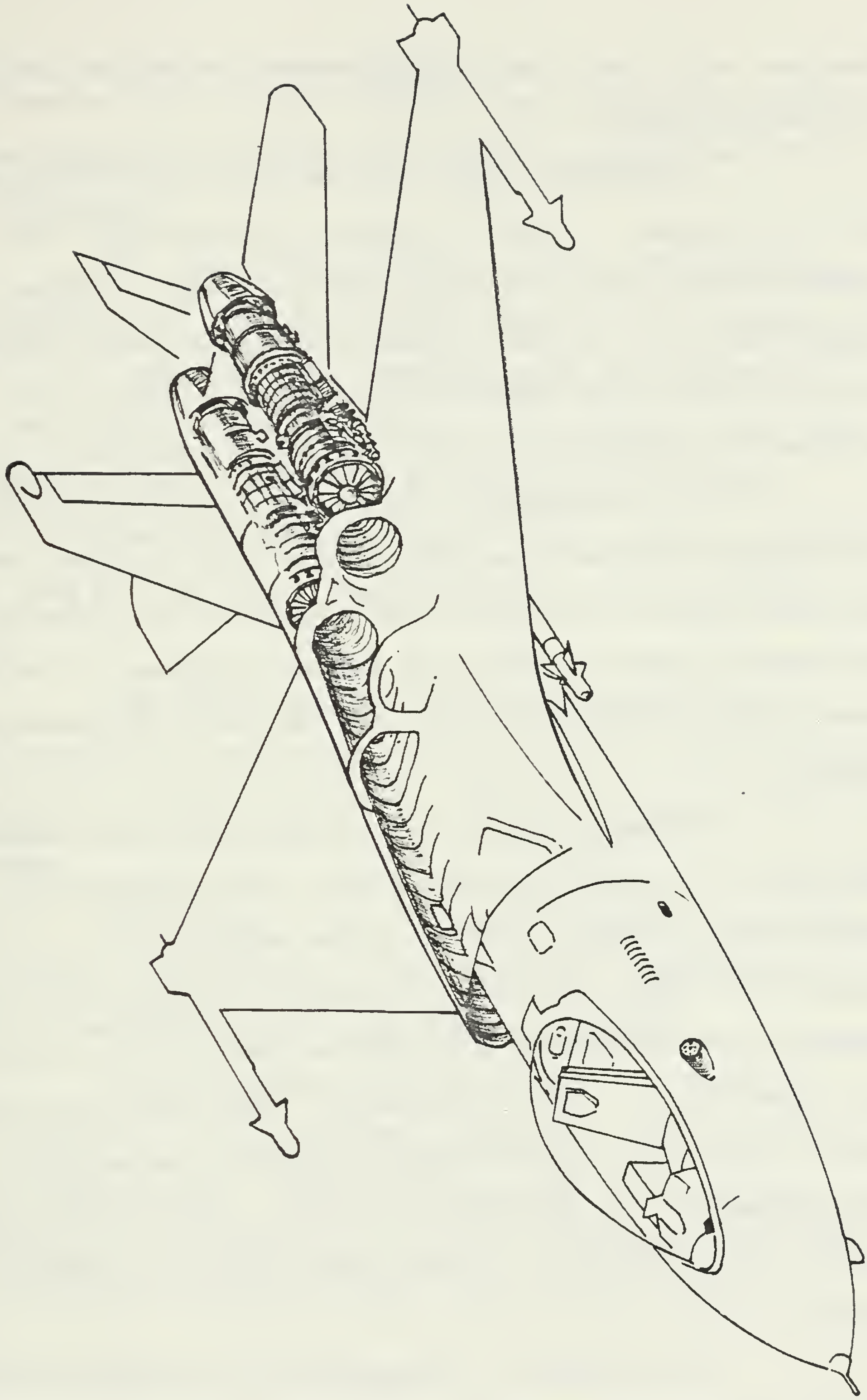


Figure 7.4 A-20 Propulsion System

fuselage, with the wings adding protection against projectile penetration.

The design engine in the A-20 is a low by-pass turbo fan engine. A three stage fan and an eight stage compressor are each driven by a single stage turbine. The compressor is of variable geometry with continuous by-pass from the fan to the augmentation section. There is no acceleration bleed system required for the engine.

For combustion, the engine is equipped with a flow through annular type combustor utilizing eight combustion cans each of which has four atomizing fuel nozzles. The burning gases are directed rearward through a single stage turbine which drives the fan and the high pressure rotors.

Augmentation is continuous and in all ranges of operation. The afterburner operates with injected fuel through six manifolds located in the exhaust core and fan discharge stream. Ignition is caused by a fuel rich mixture torching through the turbine stage to the manifold and flame holder. Fan discharge air cools the after burner liner in the duct and and helps maintain a low exterior skin temperature on the engine covers. The variable area nozzle is hydraulically actuated with its own hydraulic system.

Each engine is independently controlled with single throttle actuation by the pilot. The engine control

then programs the variable nozzle area, temperature levels, turbine speeds and correct fuel flow for proper and efficient operation.

The lubrication system is self contained for each engine. The capacity of the system is 4.5 gallons, of which 4.0 is useable. The bearing system is composed of three bearings for the fan rotor and two bearings for the high pressure rotor. The low pressure rotor bearings support the fan forward on the front frame, aft on the mid frame, and the aft end of the fan turbine in the turbine frame.

The high pressure rotor is supported by a thrust bearing at the forward end in the mid frame and by a differential bearing at the aft end of the turbine with the fan rotor.

Electrical power for engine start and electrical control is supplied by the alternator. Ignition is automatic depending on the system requirements.

The accessory gearbox drives one level of hydraulic power, the electrical generators and other miscellaneous uses. Bleed air from high and low stage compressors is utilized for auxiliary equipment operation such as engine anti-ice and the environmental control system.

e. The Armament System

The Armament System is shown in Figure 7.5. The design of the A-20 incorporates a weapons bay. Tradeoff studies revealed that the aircraft, with its unique intake system, needed the majority of the stores to be internal to sustain efficient high speed operations.

The A-20 is a heavily armed aircraft. There are four sidewinder missile mounts on the exterior; one on each wing tip and one each at the fuselage and wing underside junction.

The weapons bay has the capacity to carry either four cruise missiles or a combination of bombs/missiles with a total interior weapons load weight of 6,500 pounds. The weapons bay doors are both hydraulically and electrically actuated, and fold into themselves for drag reduction.

Mounted on the left hand interior of the fuselage, adjacent to the cockpit, is a 20 mm cannon with a capacity of 2,000 rounds per minute.

All weapons selection controls are on the pilot's control stick and throttle controls, giving him the capability to select, arm, and fire the weapon without ever taking his hands off the primary controls.

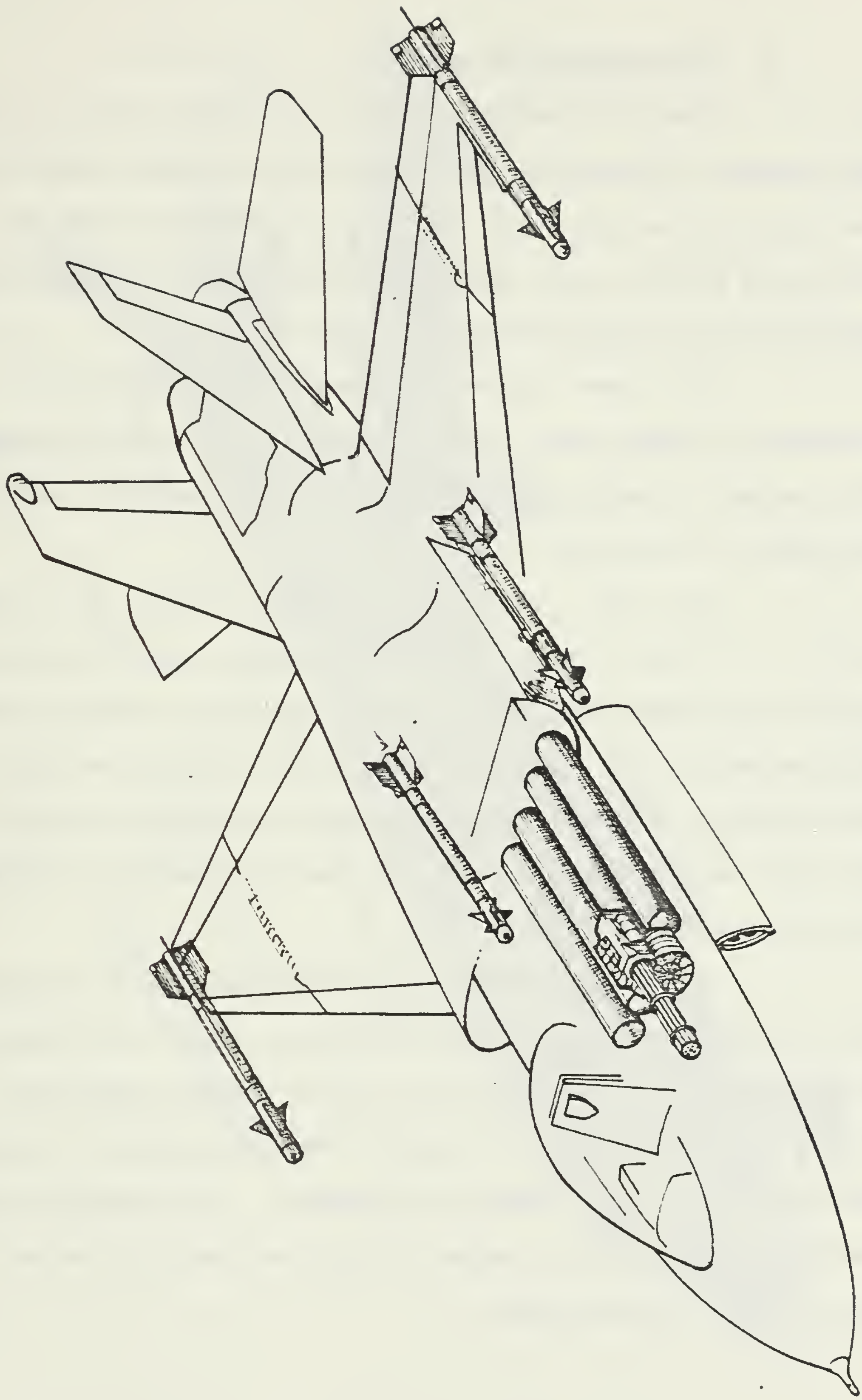


Figure 7.5 A-20 Armament System

f. The Structural System

The A-20 structure groups (Figure 7.6) are the nose radome, the weapons bay, the crew station, the forward fuselage, the center fuselage, the aft fuselage, the inboard wing section, the outboard wing section, the vertical stabilizers and the horizontal stabilators.

The nose radome provides an electronically transparent window for radar transmissions. It is a structural member, housing the forward avionics bay and semi-monocoque in construction.

The crew station is directly aft of the radome section. It has a canopy enclosed cockpit and provides an oxygen environment for the pilot. All pilot controls and features are in the cockpit. There is an ejection seat, center mounted control stick and side mounted throttles. The pilot can control all flight mission essential systems from these control mounts.

The weapons bay is located beneath and aft of the cockpit, one third of the distance along the length of the fuselage. It consists of a cavity large enough to carry four cruise missiles twelve feet in length. It is convertible to other types of ordnance. The weapons bay in itself is a structural member, built as one unit to be installed in the fuselage.

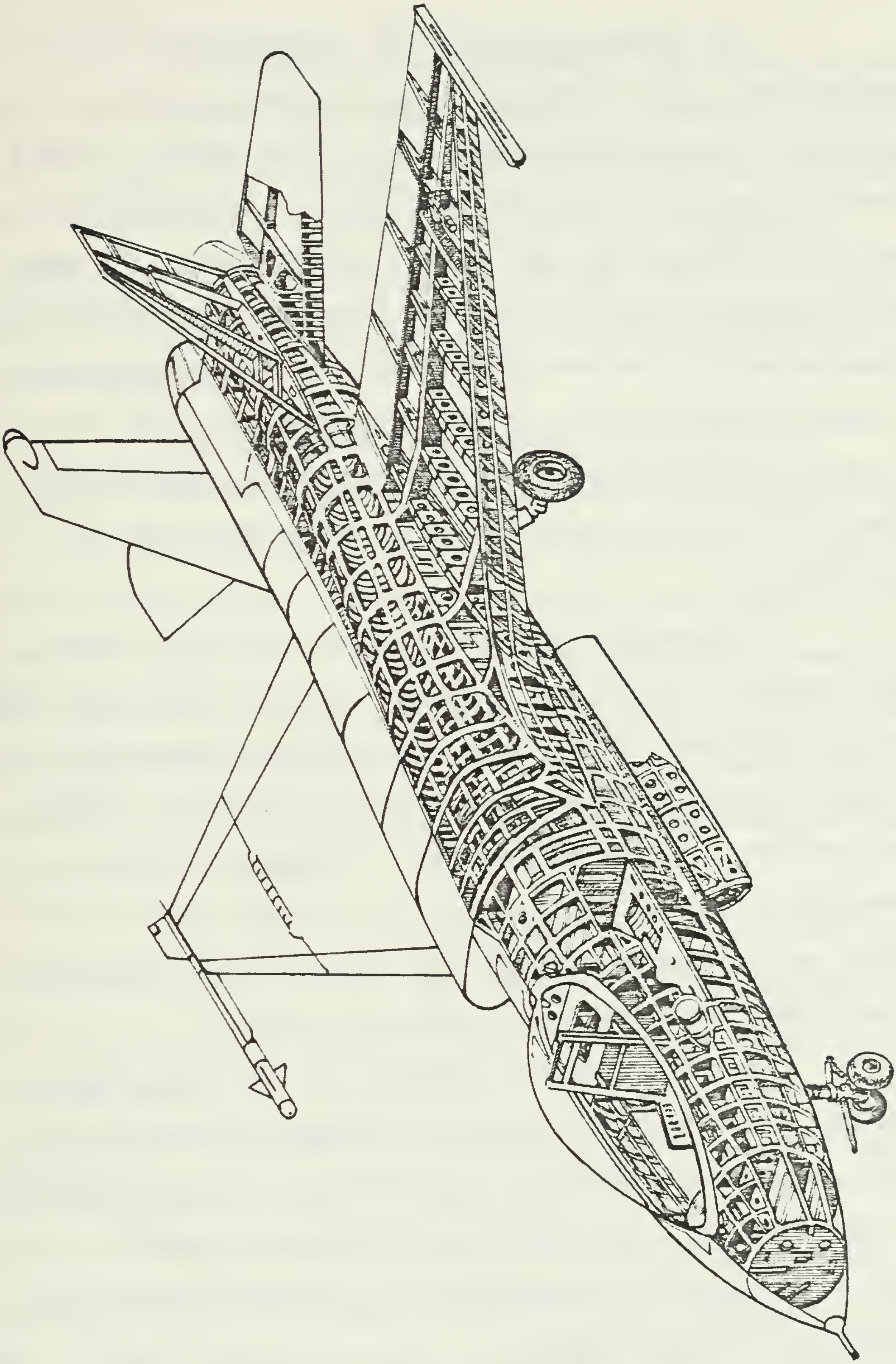


Figure 7.6 A-20 Structural System

The forward fuselage is conventionally constructed with multi-stiffened longerons and is semi-monocoque. It is strengthened for a 20 mm cannon located adjacent to the pilot on the port side. It provides a structural bulkhead for the forward avionics bay and completely supports the aft bay. It also provides attachment bulkheads for the forward portion of the weapons bay and the forward fuselage fuel tank. Structurally, the forward fuselage has major longerons, shear webs, bulkheads and floors. It is compartmented for strength and ease of maintenance.

The center fuselage carries the wrap around intake system, the forward fuselage transfer tank, the wing carry through box, roots, and wing attachment points. It also has the main landing gear supports, assorted structural members, and the aft mounting bulkhead for the weapons bay. The backup hydraulic reservoir and pump are located on the starboard side and there is also fuselage mounted sidewinder stations beneath the wing.

The aft fuselage consists of the engine bay cavities, a longitudinal alloyed bulkhead between the engines, horizontal stabilator attachments, vertical stabilizer attachments, tail hook and speed brake assembly. Also the primary hydraulic reservoirs are located adjacent to the engine accessory drives.

The inboard wing consists of the wing box, wing root, and integral fuel tank. There is a three cell torque box and the flap structure. The leading edge is extendable with the necessary hydraulic and electrical equipment located within. The wing spars and ribs are all machined and cast aluminum. The skin is both aluminum and graphite epoxy composites.

The outboard wing section consists of a multispar, multibox structure which extends from the fold joint to the wing tip. There is no fuel in this section, but it does have an outboard sidewinder installation pod located on the tip. There is also the remaining leading edge extension plumbing and an aileron which extends along the entire outboard section. The materials used in this section are primarily graphite epoxy for the skin and cast aluminum for the spars.

The vertical stabilizers are mounted with an eighty one degree dihedral on the aft fuselage assembly. They carry the vent tanks and navigation lights and consist of three spars and four box beams. The skin covering is aluminum and fiberglass. The moving control surfaces are made from graphite epoxy composites.

The horizontal stabilators are constructed entirely of graphite epoxy composites and fiberglass. They have a honey combed interior and rotate upon a titanium alloy hub.

As can be seen from the preceeding figures and discussion, the A-20 was designed for ease of major maintenance and combat damage repair.

2. Analysis Results

Consistent with the format previously established, the fuel system will be the only system broken down into detail and analyzed using the FMEA methodology to produce the final product, Table 7.1, the FMEA Matrix.

The fuel system components have been analyzed to determine how they could fail and what effect this failure has on the system. Results of the FMEA analysis performed on the fuel system are shown in Table 7.1. The most important result of this analysis is the input it provides to the preparation of the list of critical components, which is the output of the assessment.

B. A-20 DAMAGE MODE EFFECTS AND ANALYSIS (DMEA)

The DMEA is dependent upon the kill criteria and the threat. It relates potential failures such as those determined in the FMEA, with the threat weapons and their damage mechanisms. It also associates the effects of the failures to the kill criterion, redundancy and flight conditions and provides the checklist for the final determination of critical components and their redundancy relationships.

TABLE 7.1 FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON		CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
				SUBSYSTEM	MISSION		
Feed Tank	TF	provide protected fuel storage capability	gross leakage	tank not provide self-sealing capability	abort	fuel can be fed from wing tanks, pilot operated switch to shut off fuel into main feed tank	leak rate exceeds replenishment rate result is fuel level below probe, causes low fuel level indication
			minor leakage	fuel seepage	no effect		
Transfer Tank	TF	stores main fuel supply	gross leakage at fittings	cannot hold fuel supply	abort	Pilot can shut off fuel from transfer tank. Alternate plumbing for fuel from wing to feed tanks directly	
			minor leak at fittings	seepage	no effect		
Quick Disconnect, Motive Flow	TF	provide rapid applica- of motive flow lines to engines	major leakage	lose motive flow	abort, fire hazard		possible failure mode during engine replacement
			loss of mechanical integrity	unable to secure disconnect valves	extension of scheduled maintenance		
Check Valve, Motive Flow	GF,TF	restrict fuel flow to one direction	fails to relieve	no motive flow to pump	abort	valve redundancy requires failure of both in line to result in total inoperation	
			fails to check	fuel drains into engine at shutdown	no effect		

TABLE 7.1 (cont.) FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON		CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
				SUBSYSTEM	MISSION		
Fuel Lines and Fittings, Motive Flow and Transfer	TF	provide piping for motive flow to pumps	excessive leakage	lose motive flow to ejector pumps, loss of fuel	see remarks		Fuel line separate external to tank mission is aborted for fire hazard. In line separates internally, there is degradation because aircraft cannot climb to maximum altitude.
Firewall Shutoff Valve	TF	provide for fuel feed shutoff in in emergency conditions	loss of mechanical integrity	major loss of fuel	abort		
			fails to shut	pilot unable to stop fuel flow to engine	see remarks		inability to stop fuel flow to engine during emergency could result in fire, ect.
			loss of fuel flow to engine		abort		
Fuel Lines, Fuel Feed Fittings	TF	provides piping for fuel from ejector pump to engines	loss of feed path	loss of fuel	abort		

TABLE 7.1 (cont.) FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON SUBSYSTEM	FAILURE EFFECT ON MISSION	CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
Quick Disconnect Fuel Feed Line	TF	provide rapid connect/ disconnect of fuel line to engine	major leakage	reduced fuel flow to engine	abort, fire hazard		
Dual Inlet Ejector Pump	TF	provide fuel pressure from self-sealing tank to engine fuel pump	restricted flow to pump binding of one side	reduced/loss of fuel flow to pump loss of fuel to engine during negative "G" flight	abort, degraded mission		foreign matter in fuel cells causes blockage
Single Inlet Transfer Pump	TF	transfers fuel from integral tanks to transfer and feed tanks	fails to transfer	reduced/loss of fuel flow	no effect	check valve redundancy allows flow	failure due to foreign matter
Swing Check Valve, Fuel Cell	TF	three swing check valves used to keep fuel in self sealing tank at optimum	fail to check fail to relieve	low fuel level in self sealing tank remarks	no effect remarks		failure of all 3 check valves (cont)

TABLE 7.1 (cont.) FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON		CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
				SUBSYSTEM	MISSION		
		level. Aid in surge con-control					along with ejector pump failure re-sults in feed tank drain and flameout
Vent Tanks	TF	prevent fuel venting over-board. Help in surge con-trol	structural damage	improper vent-ing	abort, poss-ible fire		
Vent Drain Check Valve	TF	allows fuel to return to main fuel system	fail to check	possible fuel loss thru vent system spillage on arrestment	fire hazard fuel spills on engines and deck		
			fails to re-lieve	no effect on system	remarks	remarks	if both check val-ves fail closed, fuel can only es-cape thru vent jet-tison onto exterior instead of return-ing to system
Vent Lines and Fittings	TF	provides pip-ing for vent-ing capabil-ity	loss of mech-anical integ-rity	poor venting of vapors	no effect		

TABLE 7.1 (cont.) FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON		CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
				SUBSYSTEM	MISSION		
Vent Lines, Jettison Chutes and Fittings	TF	provide piping for fuel vent to exterior	minor leakage	seepage of vapors/fuel into fuselage	abort		fire hazard
Level Control Pilot Valves	GT,TF	regulates fueling and transfer; prevents overfill	fails to regulate fuel transfer	cannot transfer fuel or refuel in flight	mission degraded, reduces time on station		
			valves not close, tanks overfilled, vents overboard	same as above			
External Fueling Lines and Fittings	GT	interface between external tanks and main system	seepage of fuel	seepage	no effect		
Fuel Transfer System	TF	monitors and controls fuel transfer valves to automatically maintain proper proper level	electical failure	fuel cannot be transfer- properly for ground or in-flight refuel	abort		Severe center of gravity problems may arise if fuel cannot be transferred properly

TABLE 7.1 (cont.) FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON		CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
				SUBSYSTEM	MISSION		
Low Level Thermistor	TF	provides signal for low fuel condition in feed tank	indicates wet when not covered by fuel	no low fuel warning	none	monitor fuel quantity	possible increase in pilot workload, flameout if fuel useage not closely monitored
				erroneous low fuel warning light	none	monitor fuel quantity	
Filler Caps	GF,TF	provide access for gravity fueling of subsystem	mechanical damage	unable to secure cap, cannot complete gravity fueling	no effect		detected by GS personnel
Hose	TF	completes piping for motive flow and fuel feed lines to engine	loss of material integrity	loss of motive flow, fuel feed system	abort, fire hazard		
Wing Tank Interconnect Valve	TF	provides interconnect with manual shutoff valve between integral wing tanks	minor leakage	seepage between wing tanks	no effect		operation required during single engine flight to ensure entire fuel supply available
			fails to check flow	inadvertent opening of interconnect	no effect		

TABLE 7.1 (cont.) FAILURE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

GT = ground test   TF = total flight

COMPONENT	STAGE OF OPERATION	COMPONENT/ SUBSYSTEM FUNCTIONS	FAILURE MODE	FAILURE EFFECT ON		CORRECTIVE ACTION/ SAFETY FEATURES	REMARKS
				SUBSYSTEM	MISSION		
			checks flow without command	loss of interconnect	no effect		
Jettison Check Valve	TF	aids in fueling and transfer operations	fails to check	fuel tank overfill	remarks		used for ground fueling
			fail to relieve	fuel vents overboard during flight	mission degraded; reduced time on		ground abort if fueling for turnaround
				unable to jettison fuel	no effect		

Normally a DMEA is comprised of four sets of ouput data: (1) The DMEA Tables, (2) The Disablement Diagrams, (3) The Kill (or Fault) Trees or Kill Diagrams and (4) The P(k/h) Functions. In this case study all four of these data will be presented. A Fault Tree Analysis is also included in this section. As mentioned earlier, this is not required by MILSTD 2069 [Ref. 1]. It is being presented here because it is an alternate and extremely effective method of component identification.

Since the FTA is being used in this analysis, the presentation of DMEA results will be in a different order than defined by MILSTD 2069 [Ref. 1].

The results will be presented as follows: The DMEA Tables and The Disablement Diagrams are developed for the fuel system only; following the routine established in earlier sections. The FTA is presented next not only for the fuel system, but for the entire aircraft. This is done to show how effective the FTA is and to show that the depth of analysis makes it an excellent alternative to the FMEA. The list of critical components is presented in conjunction with the FTA. This was done to show how this list is the logical result and product of the FMEA, DMEA Tables, Disablement Diagrams and FTA. The Kill Tree is presented next. This is also created for the entire aircraft, giving a visual presentation of the critical components and redundancy relationships The final data presented are

P(k/h) Functions. They are presented in conjunction with a representative list of critical components from the entire aircraft. This part of the assessment is presented last to allow for input to the list from every possible source of analysis.

According to MILSTD 2069 [Ref. 1:p. 15], the list of critical components is complete after creating the DMEA Matrix. By performing the analysis of the A-20 in the order discussed, the author feels a more complete and thorough list of critical components is the end result.

1. The DMEA Matrix

The DMEA Matrix for the Fuel System is shown in Table 7.2. This matrix relates the components and their failure modes to the probability of kill given a hit functions (P(k/h)), kill criterion, and the redundancy categories in a tabular format.

As seen from Table 7.2, not all of the components of the fuel system are considered critical for the level of kill being analyzed (A-level attrition). This is one goal of the DMEA, to determine those components which are critical to the kill level of the aircraft. Table 7.2 shows the fuel system broken down into sufficient detail to allow an evaluation of its components and the role they play in the provision of essential functions.

Table 7.3 explains the notes found in the remarks section of the DMEA Matrix. This is a clarification of the

TABLE 7.2 DAMAGE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

COMPONENT	DAMAGE MODE	KILL CATEGORY		REMARKS	P(k/h)
		NON REDUNDANT A-LEVEL ATTRITION	REDUNDANT A-LEVEL ATTRITION	(See Table 7.3 for F-__ note explanations.)	
TANKS AND FUEL					
Wing Tank--Left ullage 3/4 full	Puncture/Leakage			Fire Hazard (F-1,6)	See Table 7.5 for P(k/h) values
Wing Tank--Right ullage 3/4 full					
Longitudinal Transfer Tank--Left	Puncture/Leakage	X		Fire/Explosion Hazard (F-2,3) (F-6)	
Bladder					
Fuel 0-25%		X			
Fuel 26-50%		X			
Fuel 51-75%					
Fuel 76-100%					
Longitudinal Transfer Tank--Right	Puncture/Leakage	X		Fire/Explosion Hazard (F-2,3) (F-6)	
Bladder					
Fuel 0-25%		X			
Fuel 26-50%		X			
Fuel 51-75%					
Fuel 76-100%					
Aft Transfer Tank	Puncture/Leakage			Self Sealing Tank—Fire Hazard is Reduced (F-3,6)	
Bladder					
Fuel 0-25%		X			

TABLE 7.2 (cont.) DAMAGE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

COMPONENT	DAMAGE MODE	KILL CATEGORY		REMARKS	P(k/h)
		NON REDUNDANT ATTRITION	REDUNDANT ATTRITION	(See Table 7.3 for F-__ note explanations)	
Fuel 26-50%		X			
Fuel 51-75%					
Fuel 76-100%					
Forward Feed Tank				(F-3,4,5,6)	See Table 7.5 for P(k/h) values
Bladder					
Fuel 0-25%					
Fuel 26-50%					
Fuel 51-75%					
Fuel 76-100%					
Fuel Transfer Lines and Fuel in Lines	Puncture/Sever	X		Fire Hazard (F-7)	
Line from Feed Tank to Engines			X		
Internal Lines				(F-8)	
Line from Wing to Transfer Tank			X	(F-9)	
Vent Tanks and Lines	Structural Damage	X		Vapor Hazard, Fire (F-10)	
Motive Flow Fuel Boost Pumps--Left	Mechanical/Structural Damage	X		(F-11)	
Right		X			

TABLE 7.2 (cont.) DAMAGE MODES AND EFFECTS ANALYSIS
A-20 FUEL SYSTEM

COMPONENT	DAMAGE MODE	KILL CATEGORY		REMARKS	P(k/h)
		NON REDUNDANT ATTRITION	REDUNDANT ATTRITION	(See Table 7.3 for F-__ note explanations)	
Fuel Transfer--Motive Flow Lines	Puncture/Sever	X		Fire Hazard See FMEA Table 6.1	
Fuel Boost Motive Flow Lines	Puncture/Sever	X		Fire Hazard See FMEA Table 6.1	See Table 7.5 for P(k/h) values
Engine Fuel System--Left and Right	Puncture/Structural Damage		X	Attrition if both left and right systems fail. See FMEA Table 6.1	
Engine Driven Fuel Pump			X		
Fuel Temperature Cont.			X		
Fuel Filter			X		
Firewall Shutoff Valve					
Ejector Pump			X		
Swing Check Valve			X		

TABLE 7.3 FUEL SYSTEM DMEA NOTES

F-1: Component not critical for vulnerable area calculations.

F-2: Location adjacent to weapons bay makes this tank very important in vulnerable area calculations.

F-3: Ullage is considered only when tank is less than 50% full.

F-4: Tank has "get home" fuel, can feed both engines if necessary.

F-5: Tank is kept full by auto-sequencing of fuel system.

F-6: Bladders and Tanks themselves are not considered critical for vulnerable area calculation.

F-7: Lines from feed tank to engines are redundant. Allows feeding of both engines.

F-8: Most of fuel lines are internal and short as seen in Figure [7.1]. Rupture of line will not affect flow in majority of system.

F-9: Each wing tank has two paths to flow to engine. Can direct feed is necessary.

F-10: Either vent tank capable of venting system. Vent hazard is small. Area is not considered in vulnerable area calculation.

F-11: Loss of both pumps results in fuel starvation because of inability to transfer.

effect the damaged component has on the system. Notice that several of the remarks refer to the FMEA, an example of the interrelationship between the types of assessment.

2. The Disablement Diagram

The second set of data developed in the DMEA is the Disablement Diagram. The Disablement Diagram combines both data from the FMEA and DMEA to display:

1. The physical location of components within the system.
2. The failure mode of a component.
3. The effect of the failure on the subsystem and the aircraft.
4. The resultant aircraft kill criteria.

Figure 7.7 show the Fuel System Disablement Diagrams. The components and subsytems that can if killed would lead to an attrition kill are exhibited graphically in flow chart fashion. Note the redundancy in the motive flow pumps and engine driven fuel systems.

3. The Fault Tree Analysis (FTA)

The Fault Tree Analysis, (the output of which is known as the Fault Tree Diagram or Failure Analysis Logic Tree {FALT}), is not specifically required by MILSTD 2069 [Ref. 1] as a means of determining the critical components of the system. However, it is often used as a substitute for the FMEA when one is not available. Because of its use as one of the principal tools of system safety, reliability and maintainability analyses, it may be preferred over the

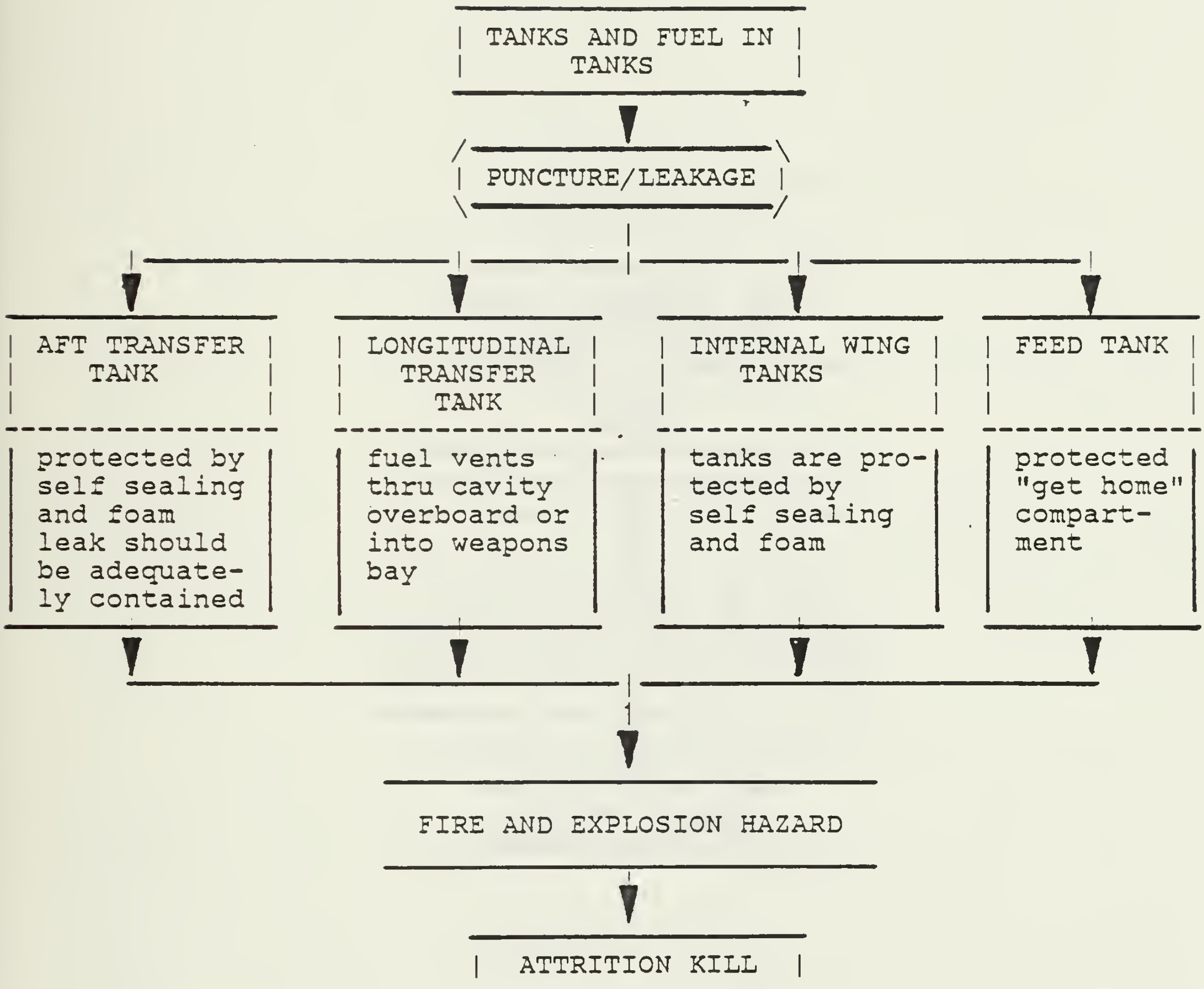


Figure 7.7 A-20 Fuel System Disablement Diagram

FUEL TRANSFER LINES/
FUEL IN LINES

↓

PUNCTURE/SEVER/LEAKAGE

↓

FUEL SPILLAGE--FIRE HAZARD

↓

ATTRITION KILL

Figure 7.7 (cont.) A-20 Fuel System Disablement Diagram

MOTIVE FLOW FUEL BOOST PUMPS

↓

STRUCTURAL/MECHANICAL DAMAGE

↓

REDUCTION/LOSS OF FUEL

↓

engine fueled by cross feed unless both systems damaged

↓

ATTRITION KILL

Figure 7.7 (cont.) A-20 Fuel System Disablement Diagram

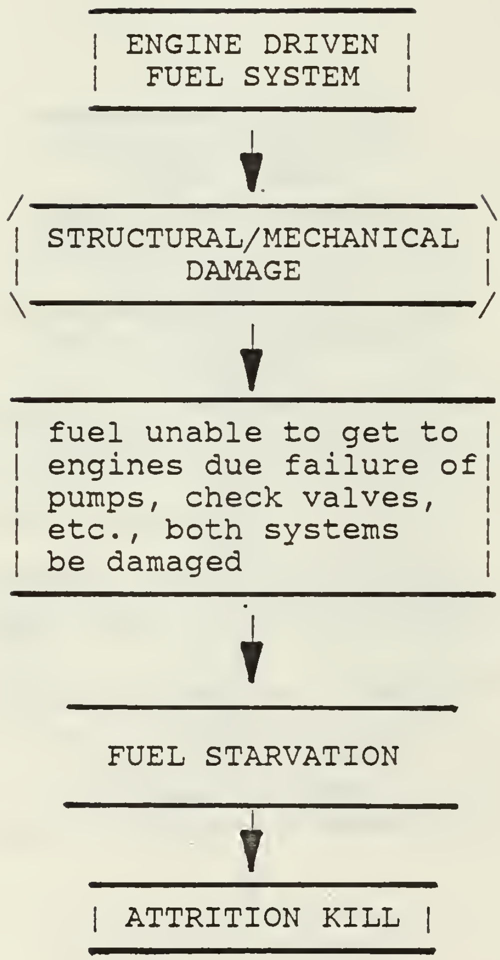


Figure 7.7 (cont.) A-20 Fuel System Disablement Diagram

FMEA. This analysis is valuable in that its logic and methodology involves development of a system hierarchy in terms of a specific characteristic, result or effect. As such it can take into account both hardware failures and human effects.

The FTA begins with an undesired event, in this case study an A-level attrition kill. It then logically determines what event or combination of events (i.e., component or subsystem failures due to penetrator damage) can cause the undesired event to occur.

For most aircraft FTA's, attrition is caused by the inability of the aircraft to fly or land. For the A-level attrition, only the inability of the aircraft to fly is analyzed. The assessment then logically branches down into a detailed analysis of what can cause the attrition. Ball [Ref. 2] discusses the FTA and its logic symbology on pages 149-151.

Figure 7.8 and Table 7.4 show the results of the Fault Tree Analysis performed on the A-20. The Fault Tree Diagram or FALT is the graphical presentation of the analysis. Figure 7.8 shows the aircraft and its subsystems broken down, just like in an FMEA, to determine how the undesirable event, the A-level attrition, can occur.

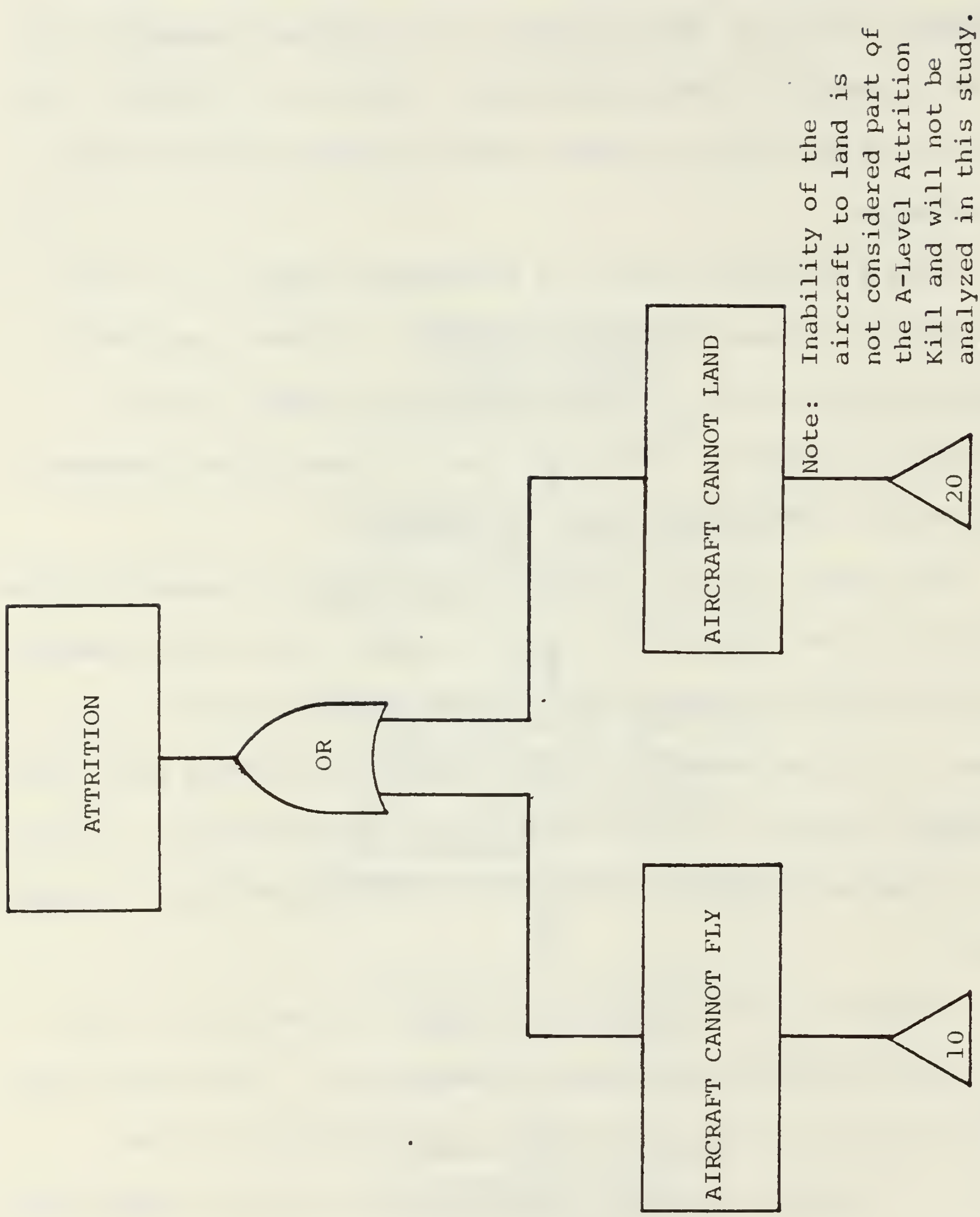


Figure 7.8 A-20 Fault Tree Diagram

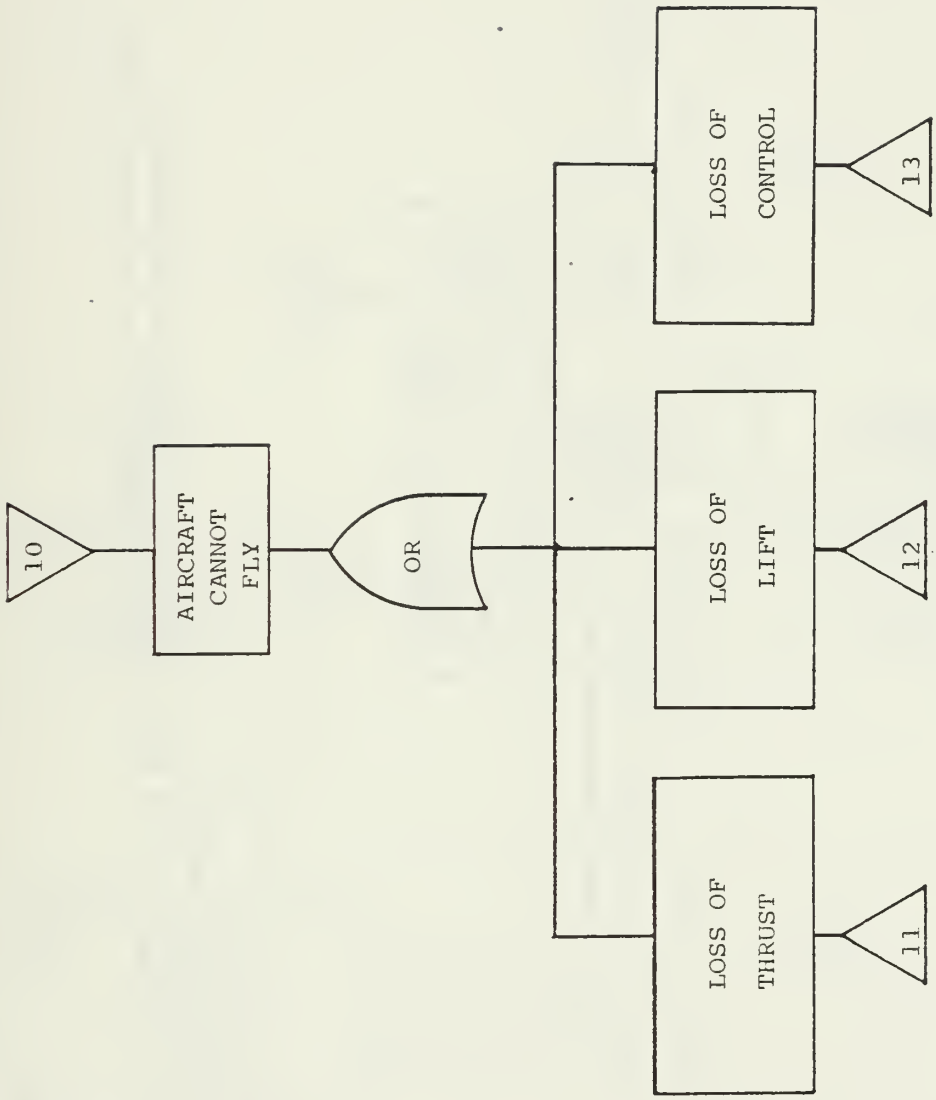


Figure 7.8 (cont.) A-20 Fault Tree Diagram

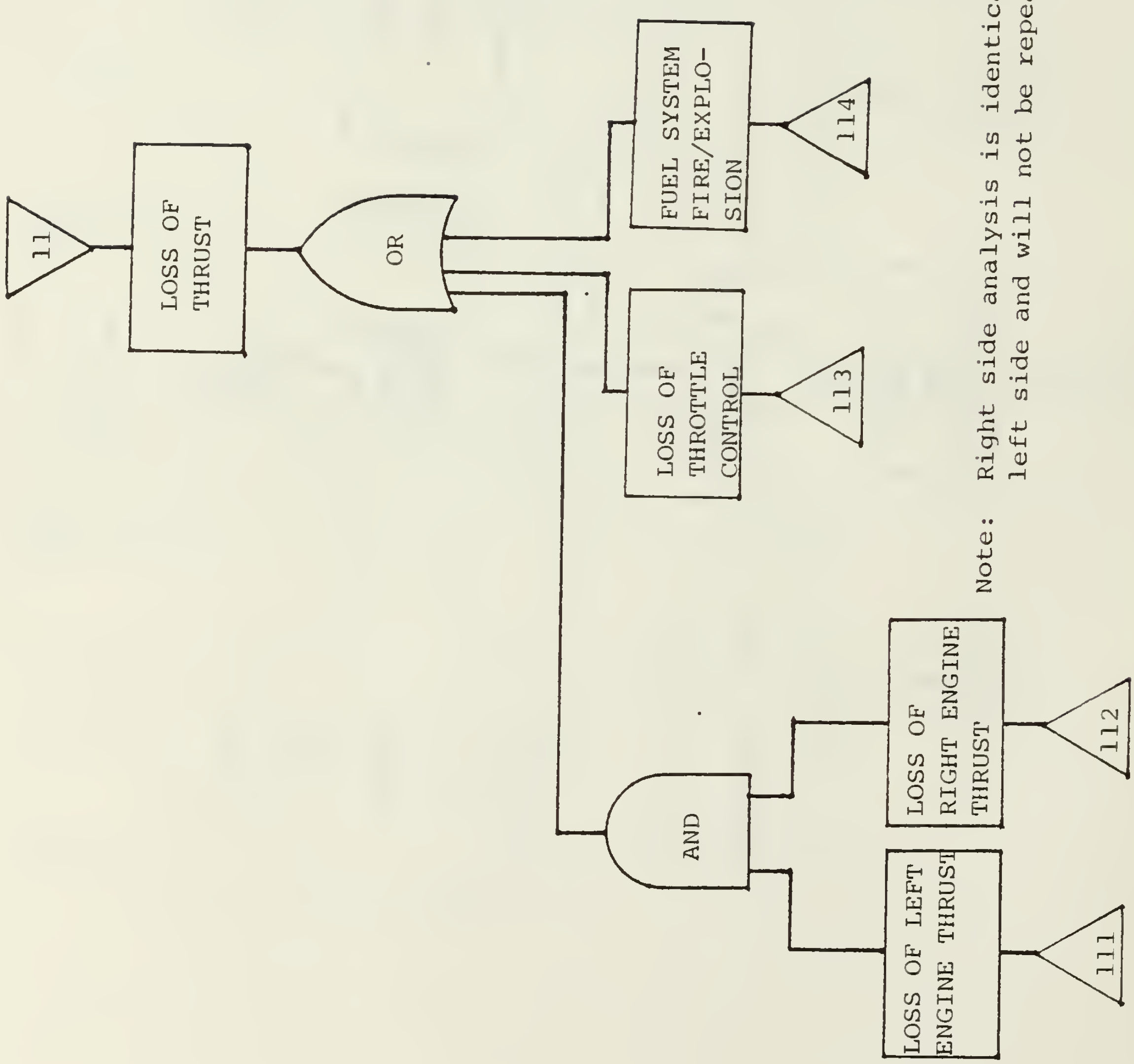


Figure 7.8 (cont.) A-20 Fault Tree Diagram

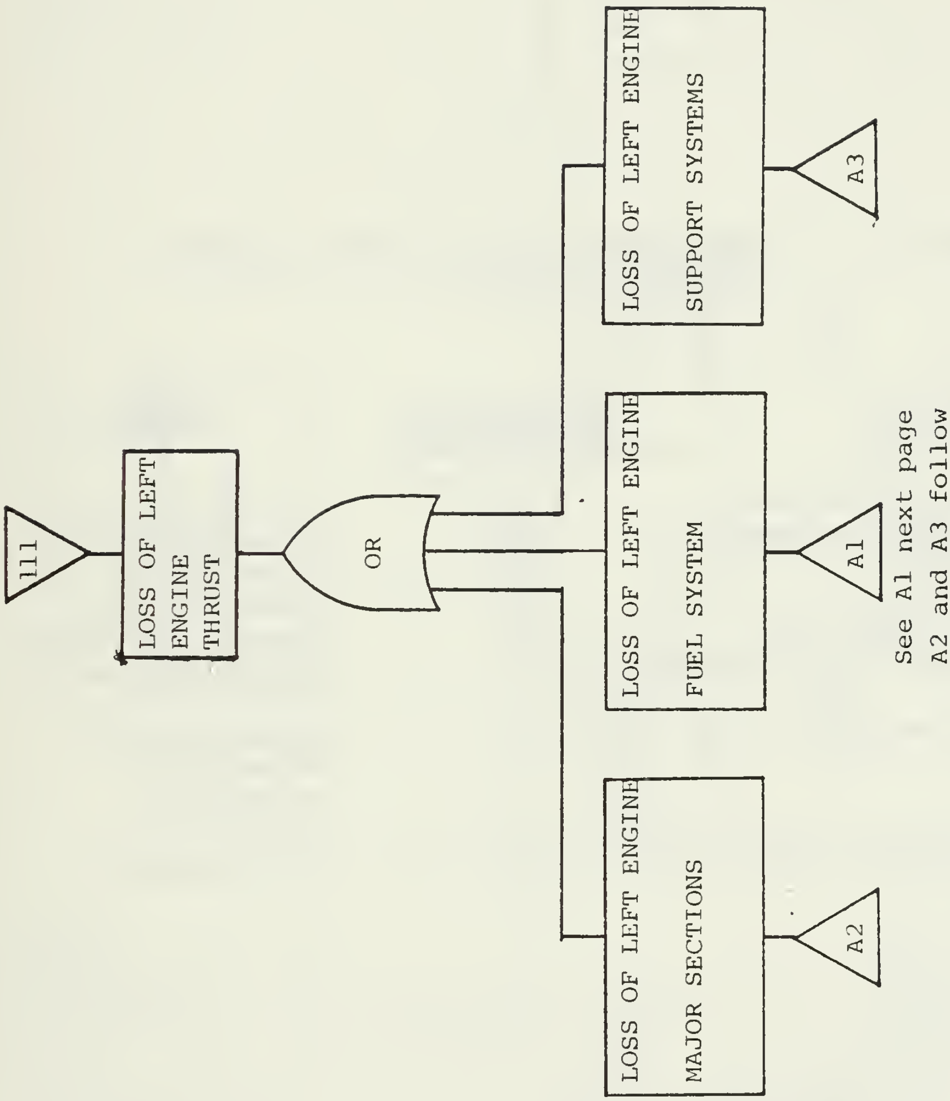


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 A1 LEFT ENGINE FUEL SYSTEM FAILURE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
engine driven fuel pump	R	penetration
fuel temperature control	R	penetration
fuel control	R	penetration
fuel nozzles	R	penetration
motive flow fuel line	R	penetrate/sever
fuel line-feed tank to engine	R	penetrate/sever
swing check valve	R	penetration--three for attrition
firewall shutoff valve	R	penetration

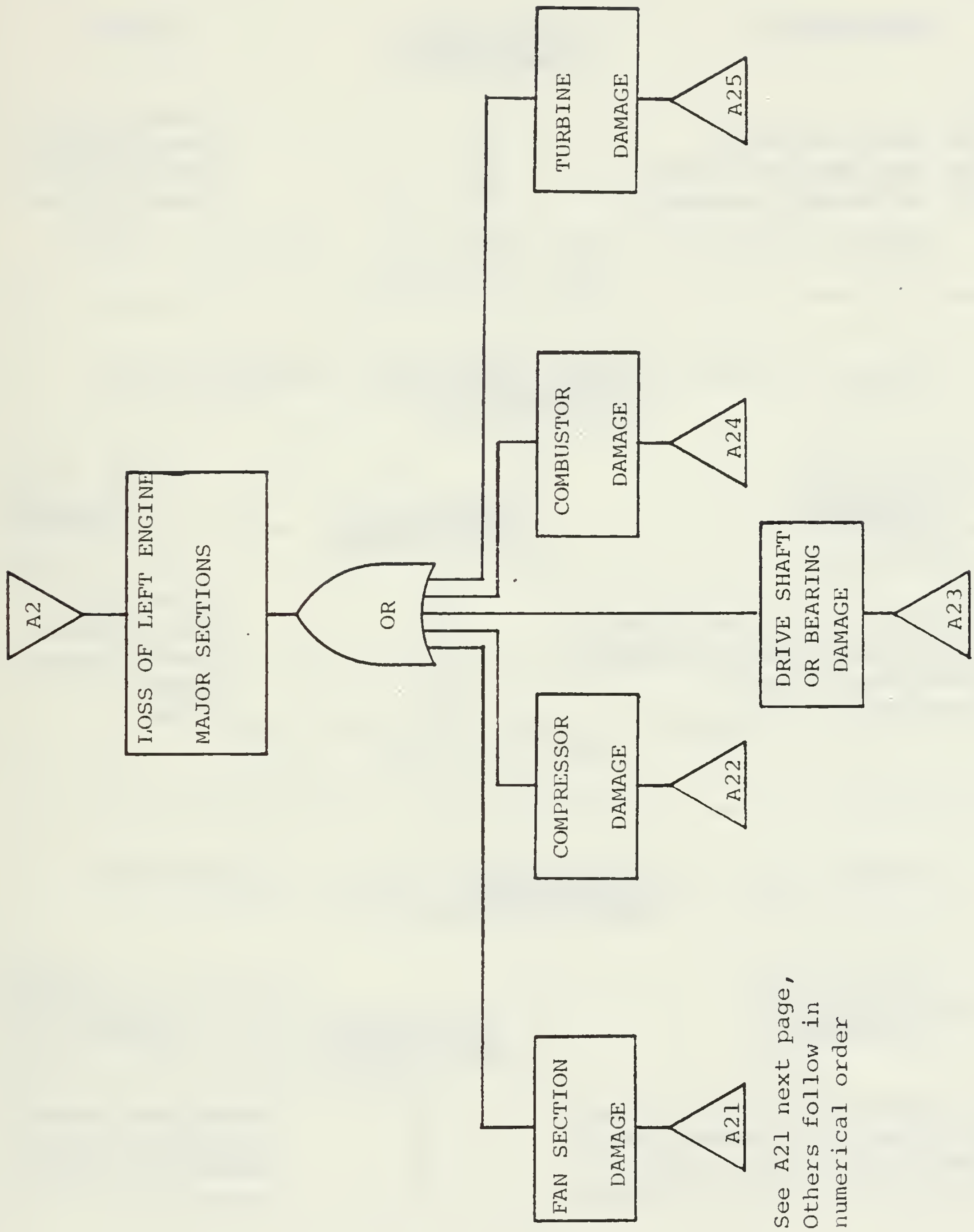


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) A21 LEFT ENGINE FAN SECTION DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
case	R	penetration
inlet case supports	R	penetration
rotor and stator blades	R	penetration
front accessory support	R	penetration

A22 LEFT ENGINE COMPRESSOR DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
case	R	penetration
LP rotor and stator blades	R	penetration
HP rotor and stator blades	R	penetration
LP compressor hub	R	sever
HP compressor hub	R	sever

A23 LEFT DRIVE SHAFT AND BEARING DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
LP turbine/compressor shaft	R	penetrate/sever
HP turbine/compressor shaft	R	penetrate/sever
forward end thrust bearing	R	penetrate/sever
aft end differential bearing	R	penetrate

TABLE 7.4 (cont.) A24 LEFT ENGINE COMBUSTOR DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
outer case	R	penetration
inner case	R	penetration
combustion chamber duct	R	penetration
bypass duct	R	penetration

A25 LEFT ENGINE TURBINE DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
case	R	penetration
hp bypass air duct	R	penetration
hp bearing supports	R	penetrate/sever
hp rotor and stator blades	R	sever
lp rotor and stator blades	R	sever

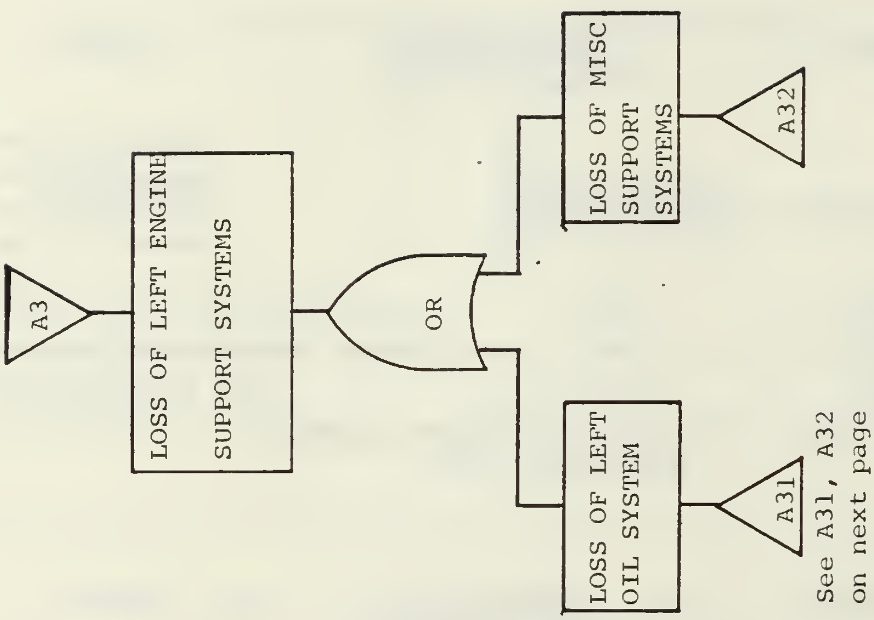


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) A31 LEFT ENGINE OIL SYSTEM DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
scavenge pump drive shaft	R	sever
main gear box	R	penetration
lube oil scavenge pump	R	penetration/ starvation

A32 LEFT ENGINE SUPPORT SYSTEM DAMAGE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
inner inlet duct	R	penetration-- fuel ingestion
engine mount(s) forward mid rear	R	sever 2 or more for attrition
throttle actuator	R	sever/penetrate
support control box	R	penetration
bleed control	R	penetration

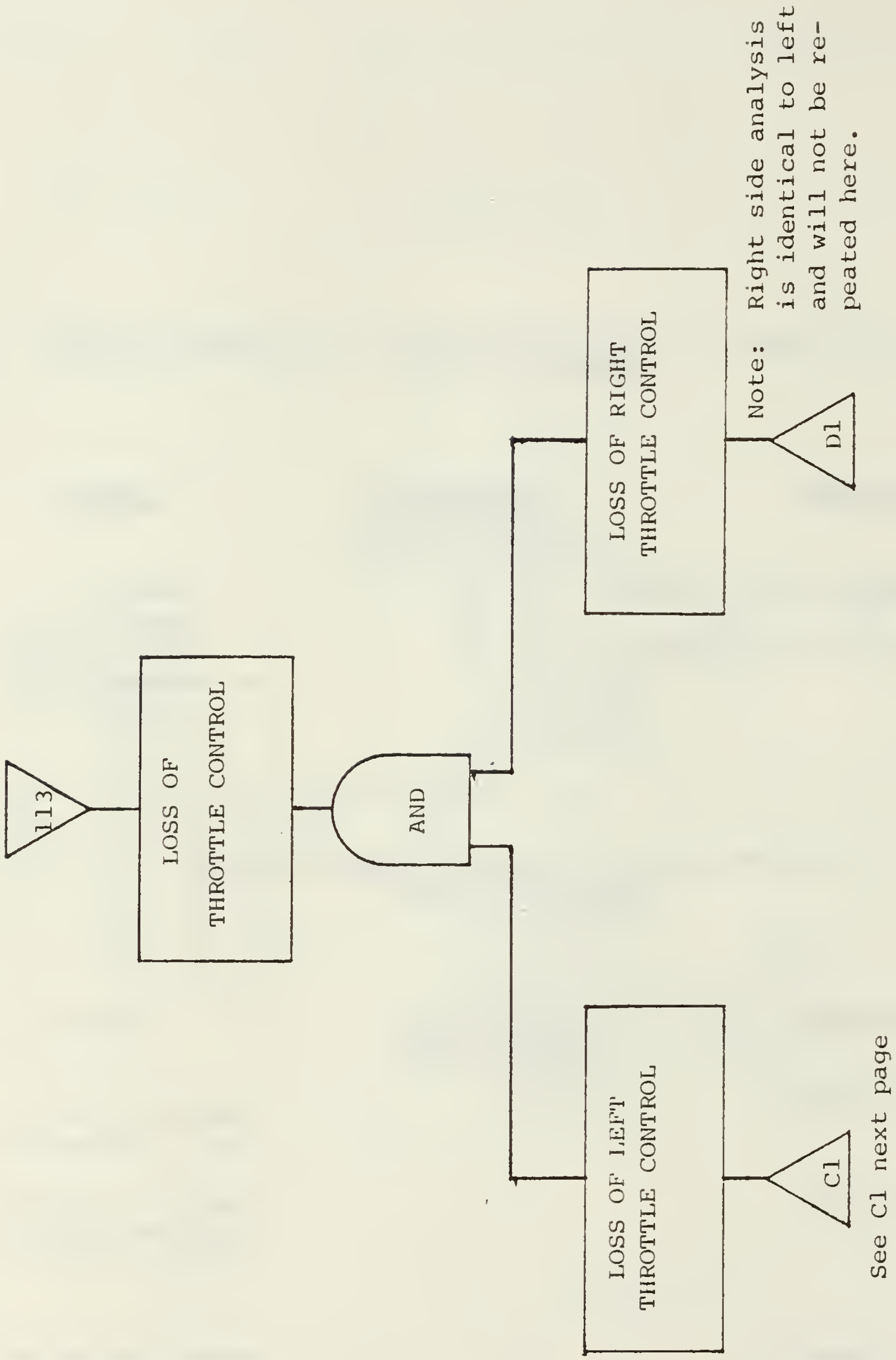


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) C1 LOSS OF LEFT ENGINE THROTTLE CONTROL COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
throttle control	R	jam/sever

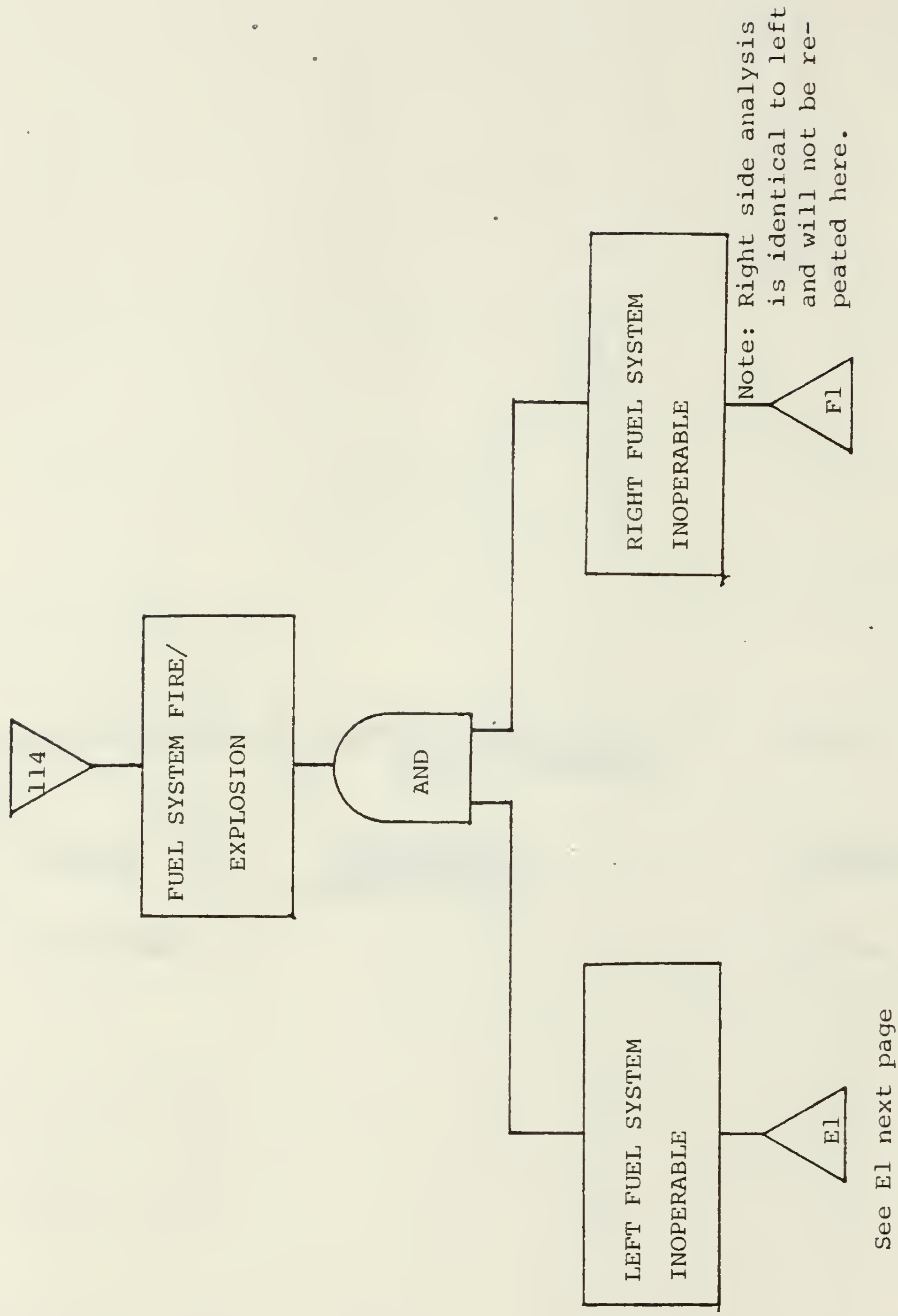


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) E1 LEFT FUEL SYSTEM INOPERABLE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
wing tank	NR	fire/explosion
longitudinal transfer tank	NR	hydraulic ram
0-25% fuel	NR	fire/explosion
26-50% fuel	NR	fire/explosion
forward feed tank	NR	hydraulic ram
aft transfer tank	NR	hydraulic ram
vent tank	NR	structural damage
fuel transfer lines	R	puncture/sever
motive flow lines	R	puncture/sever

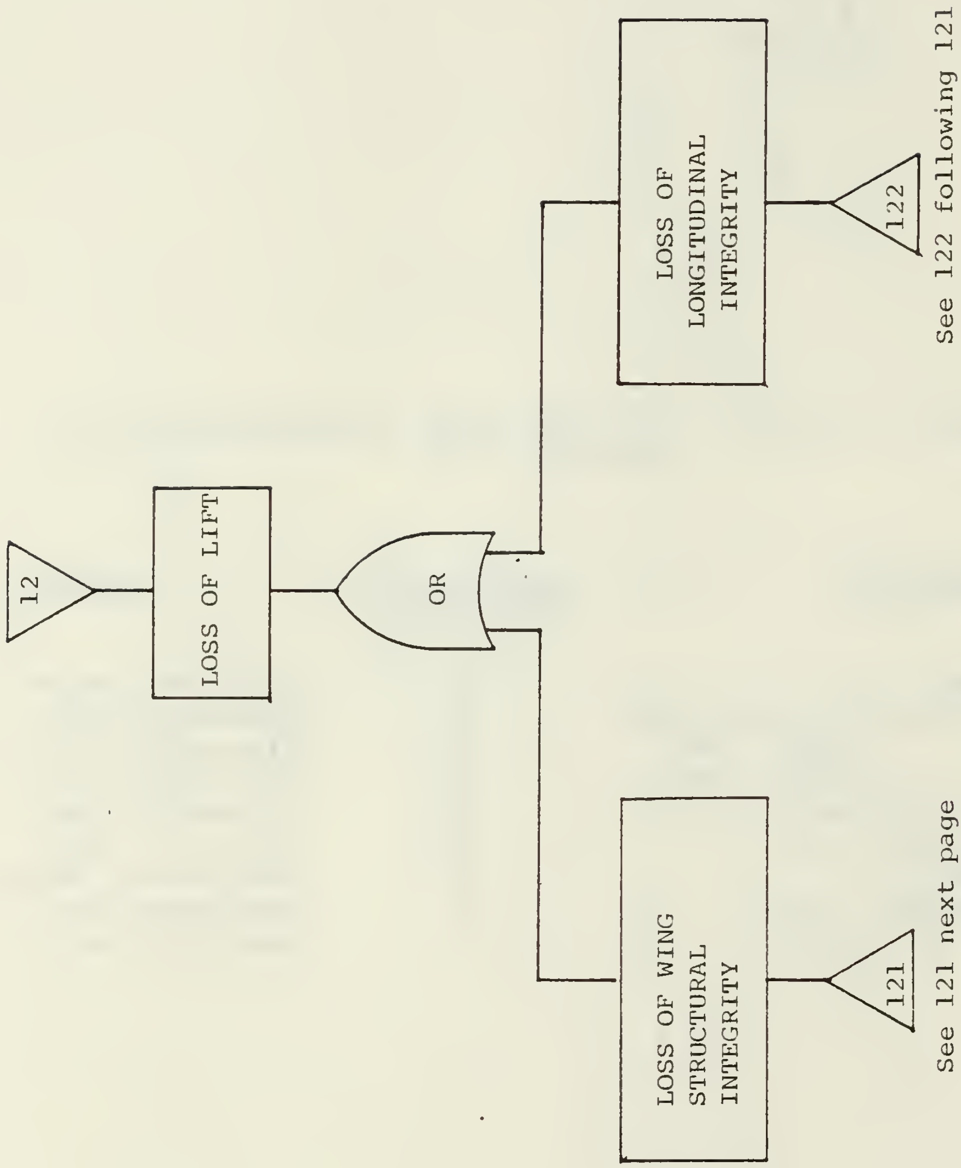


Figure 7.8 (cont.) A-20 Fault Tree Diagram

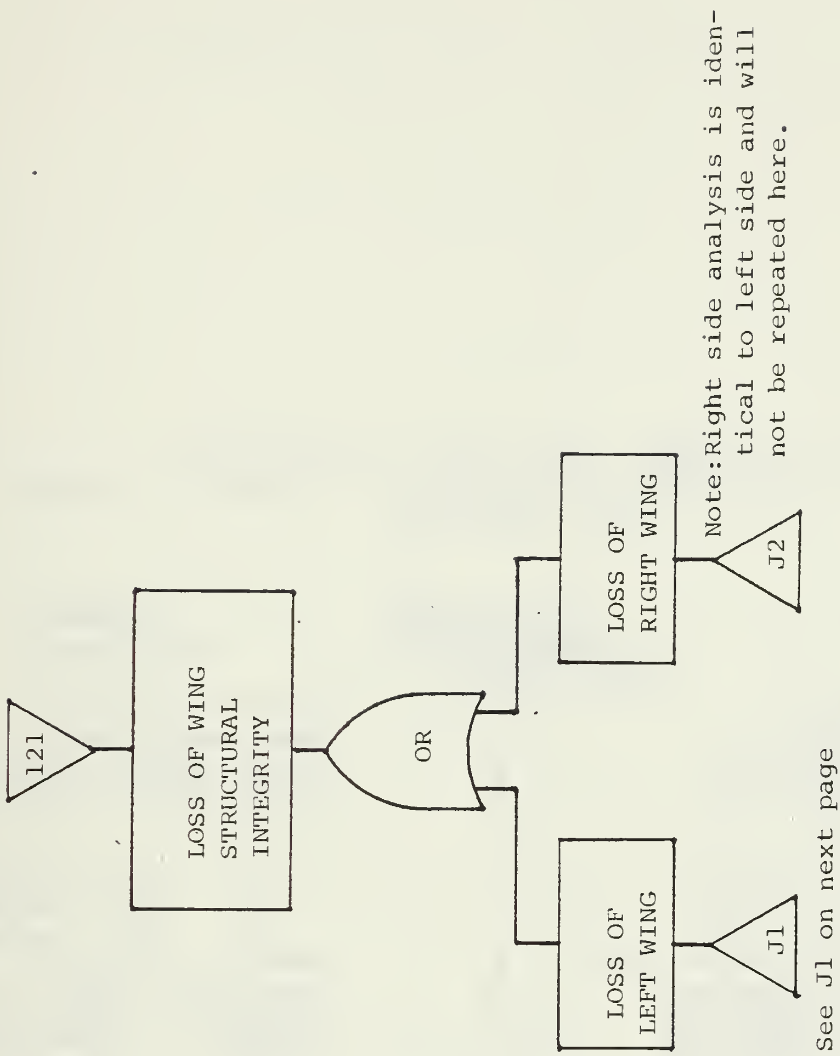


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) J1 LOSS OF LEFT WING
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
left front spar cap	R	sever, hydraulic
left aft spar cap	R	ram--must lose
left #1 spar cap	R	three of six for
left #2 spar cap	R	attrition
left #3 spar cap	R	
left #4 spar cap	R	
left front outboard spar cap	R	sever, hydraulic
left #1 outboard spar cap	R	ram--must lose
left #2 outboard spar cap	R	three of five for
left #3 outboard spar cap	R	attrition
left rear outboard spar cap	R	

TABLE 7.4 (cont.) 122 LOSS OF LONGITUDINAL INTEGRITY COMPONENT LIST

COMPONENT		REDUNDANCY RELATIONSHIP	DAMAGE
forward upper	(2)	R	sever--must sever
forward lower	(2)	R	three of six for
forward aft	(2)	R	attrition
center upper	(2)	R	sever--must sever
center lower	(2)	R	three of six for
center keel	(2)	R	attrition
aft upper	(2)	R	sever--must sever
aft side	(2)	R	three of six for
aft keel	(2)	R	attrition

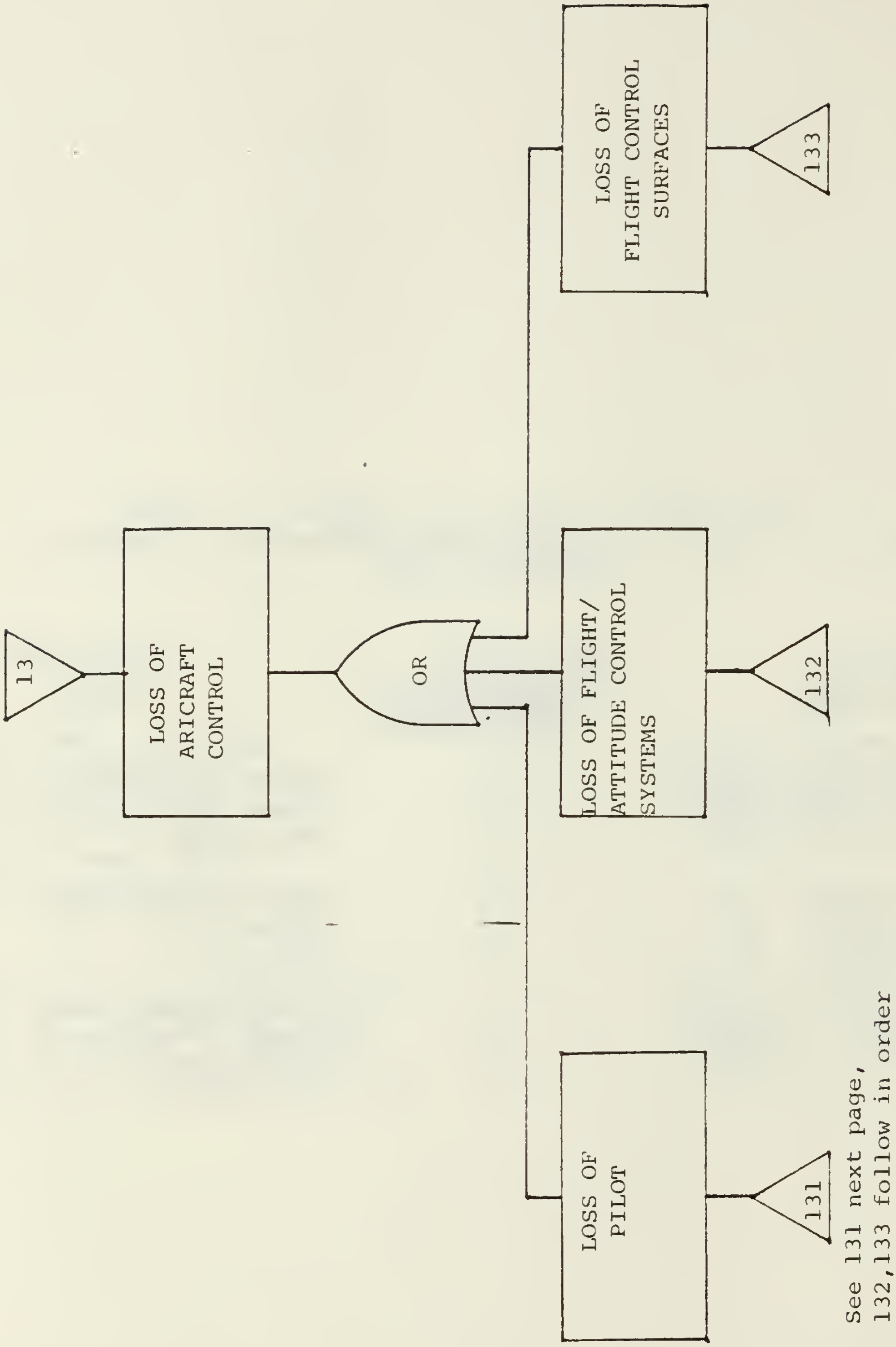


Figure 7.8 (cont.) A-20 Fault Tree Diagram

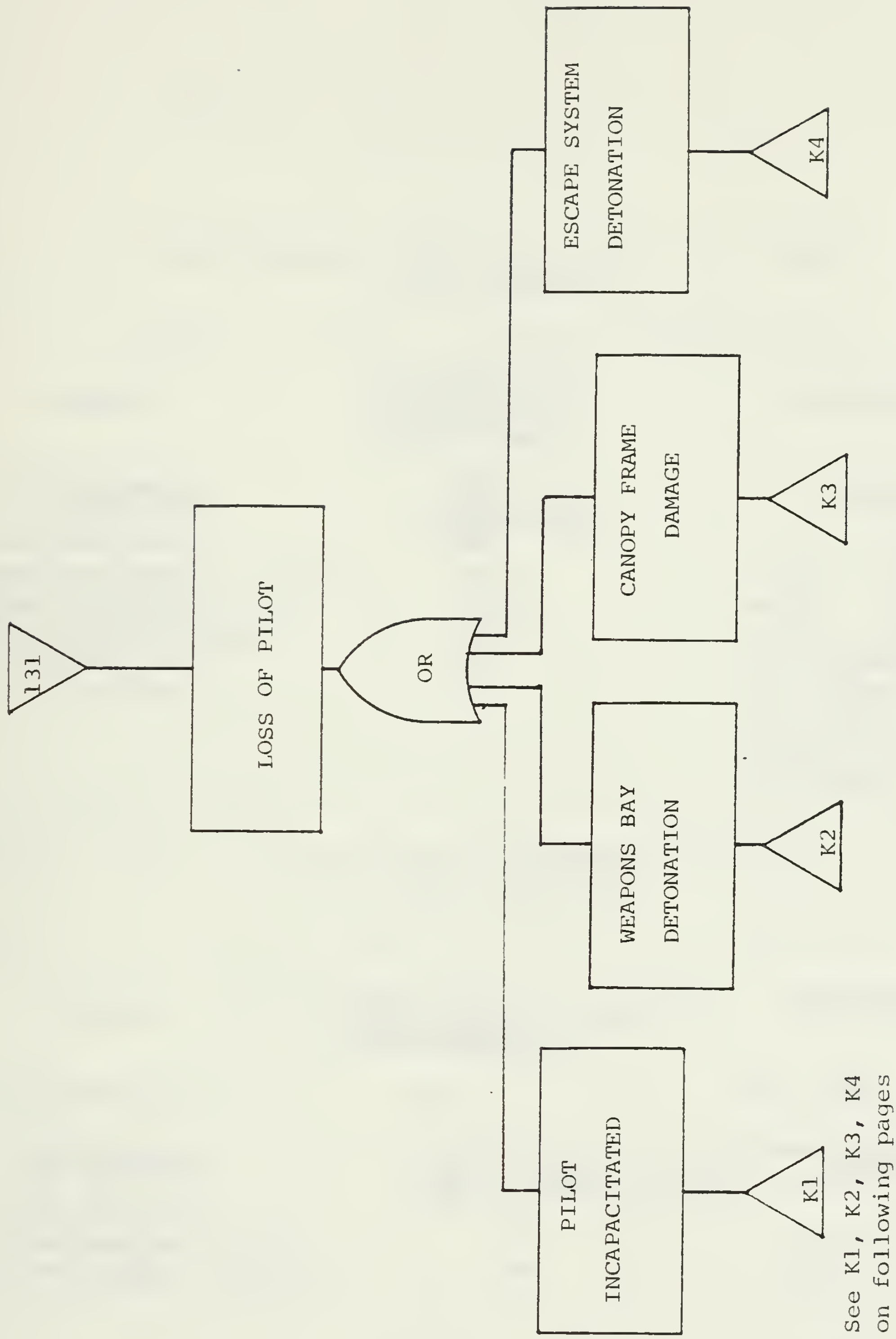


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) K1 PILOT INCAPACITATED
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
head	NR	penetration
thorax	NR	penetration
abdomen	NR	penetration
pelvis	NR	penetration
left arm	NR	penetration
left leg	NR	penetration
right arm	NR	penetration
right leg	NR	penetration

K2 WEAPONS BAY DETONATION
COMPONENT LIST

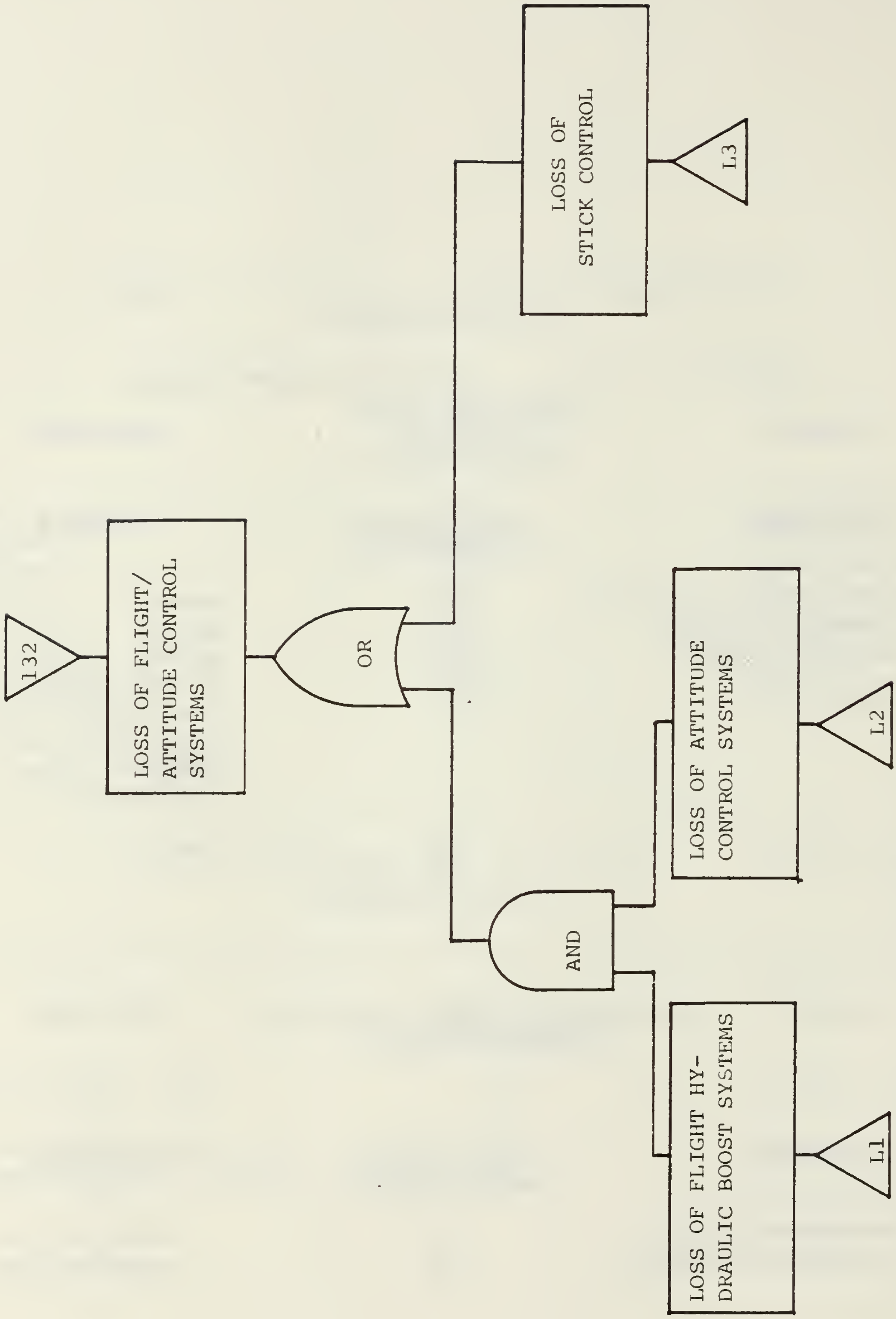
COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
cannon ammo drum	NR	penetration
missile warheads (4)	R	penetration
missile rocket motors (4)	R	of any one of the eight can cause attrition

TABLE 7.4 (cont.) K3 CANOPY FRAME DAMAGE
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
forward canopy support	NR	sever
mid canopy support	NR	sever
aft canopy support	NR	sever if more than one support severed, pilot assumed incapacitated
canopy hinge	NR	sever

K4 ESCAPE SYSTEMS DETONATION
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
pilot oxygen bottle	NR	penetration
pilot rocket catapult	NR	penetration



See L1 next page, L2 and L3 follow in order

Figure 7.8 (cont.) A-20 Fault Tree Diagram

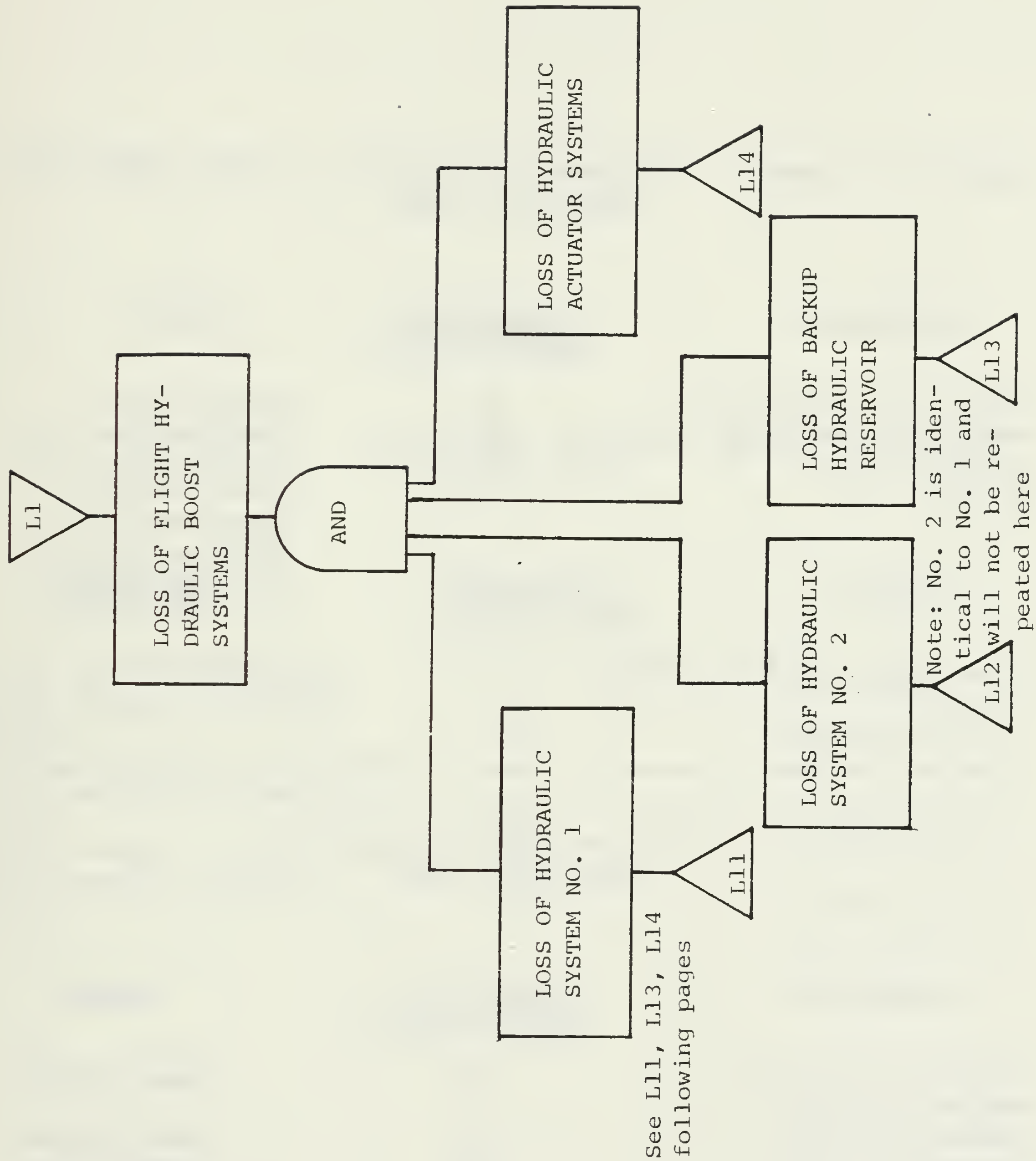


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) L11 LOSS OF HYDRAULIC SYSTEM NUMBER ONE COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
hydraulic accumulator	R	penetration
engine driven pump	R	penetration
circuit 1A	R	penetration
circuit 1B	R	penetration penetration must occur in both circuits to lose system
switching and flow sensor	R	penetration

L13 LOSS OF BACKUP RESERVOIR COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
backup reservoir	NR	penetration
switching and sensing monitor	NR	penetration
pressure lines	NR	penetration
return lines	NR	penetration
flow transducer	NR	penetration

TABLE 7.4 (cont.) L14 LOSS OF HYDRAULIC ACTUATOR SYSTEMS COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
left aileron actuator	R	penetration
left aileron sensing valve	R	penetration
left stabilator actuator	R	penetration
left stabilator sensing valve	R	penetration
left rudder actuator	R	penetration
left rudder sensing valve	R	penetration

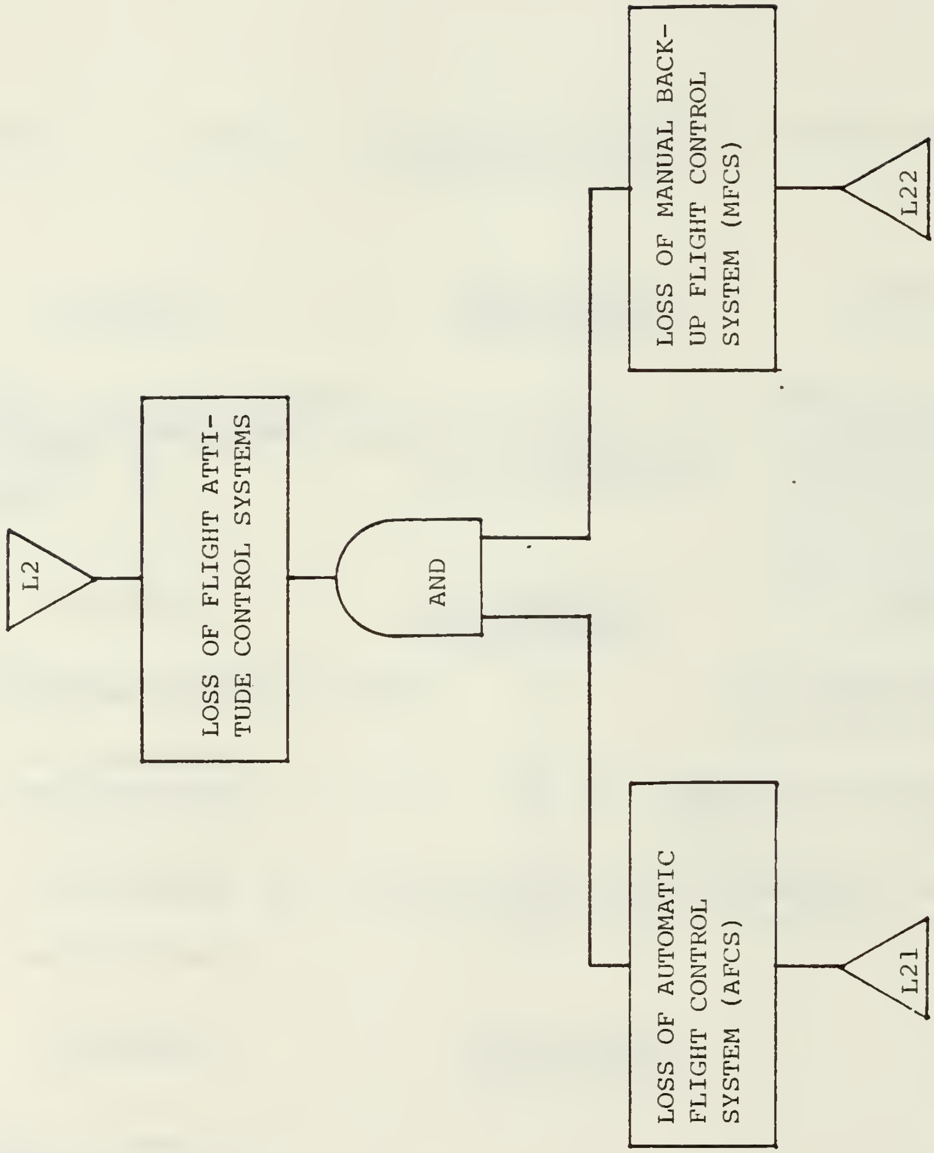


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Figure 7.8 (cont.) A-20 Fault Tree Diagram

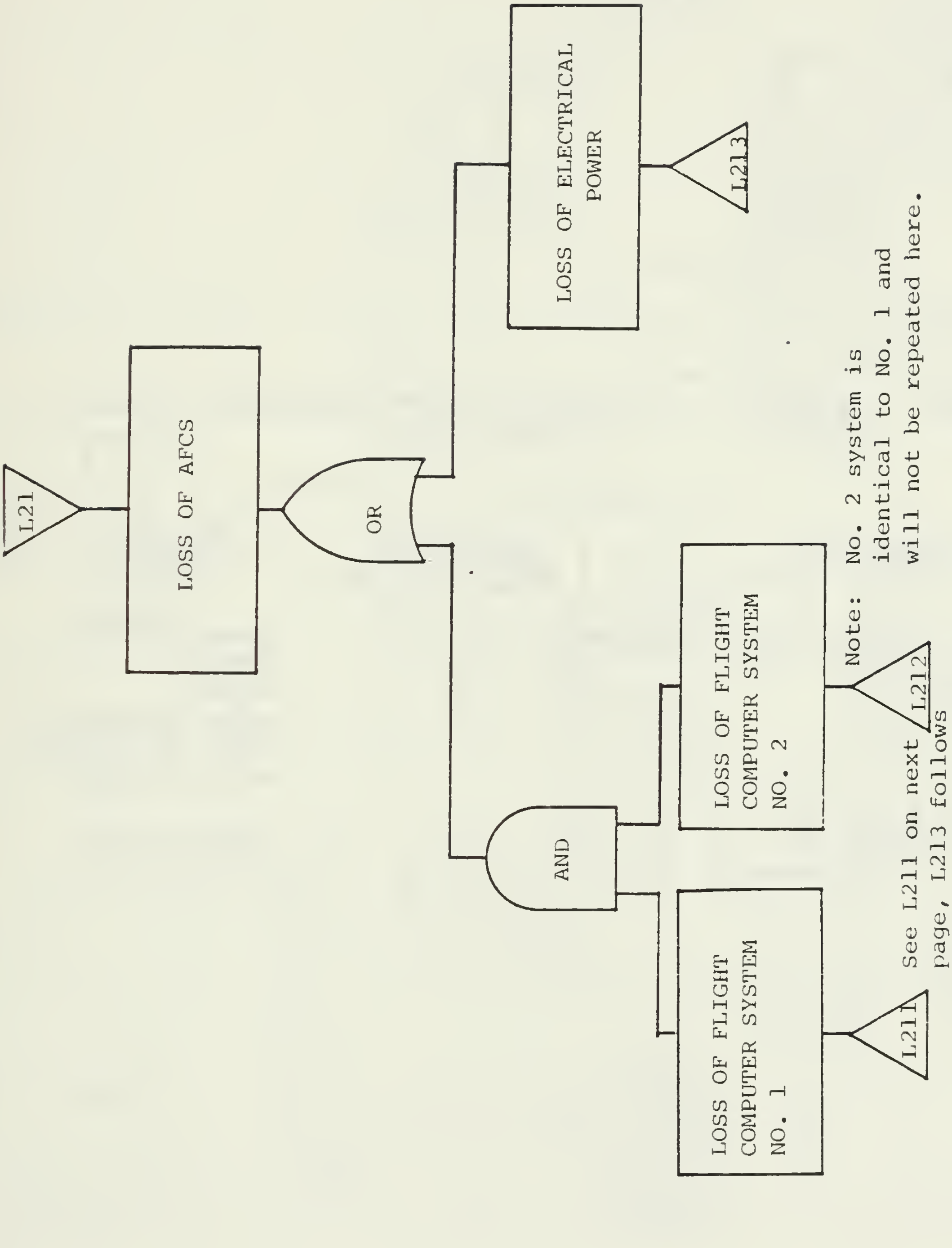


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) L211 LOSS OF FLIGHT COMPUTER SYSTEM NO. 1
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
gyro stabilization system	R	penetration
channel 1A	R	sever
channel 1B	R	sever both channels must be severed for loss
accelerometer	R	penetration
rate/motion sensor	R	penetration

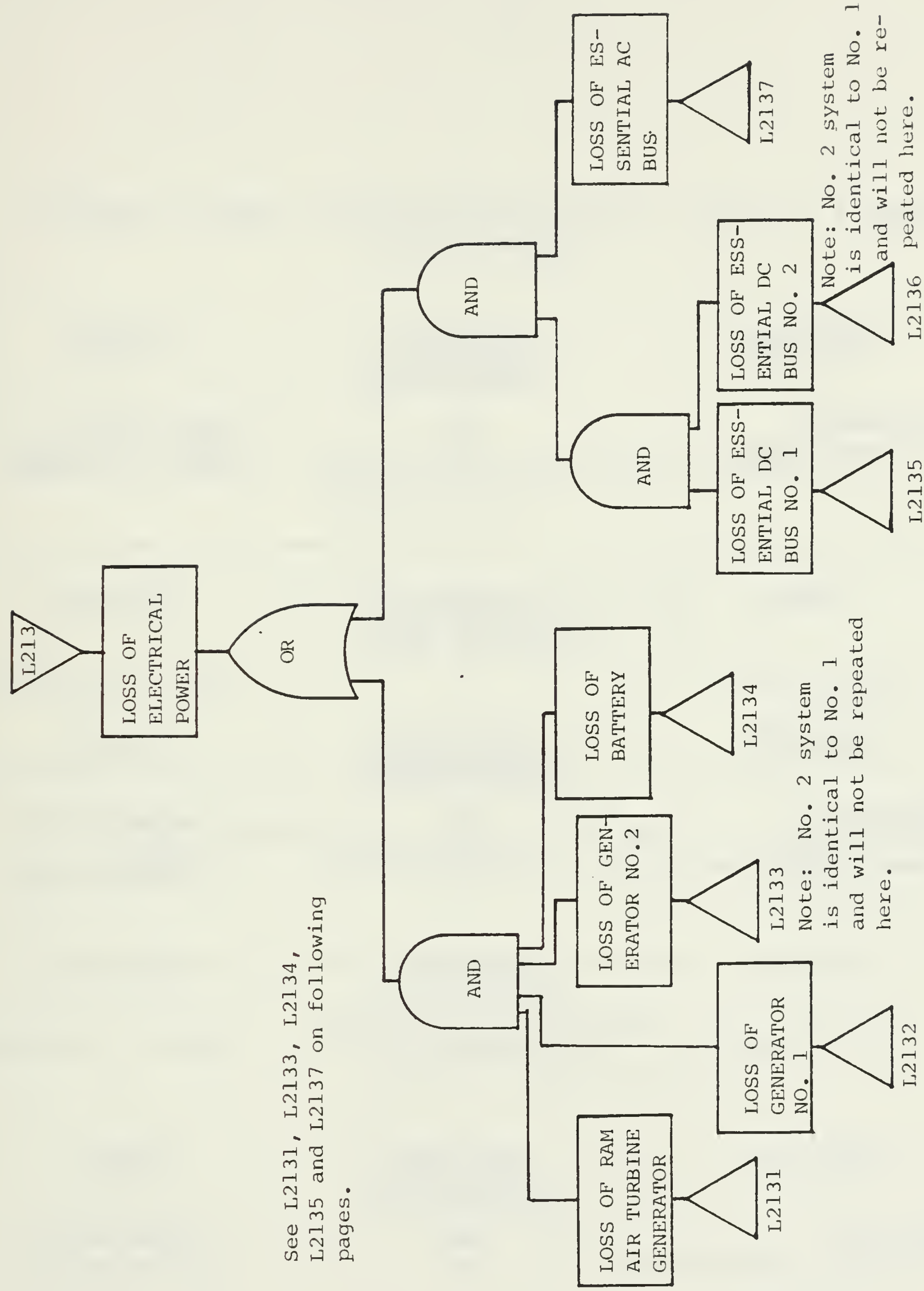


Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) L2131 LOSS OF RAM AIR TURBINE GENERATOR COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
generator	NR	penetration
actuator door	NR	jam/penetration

L2132 LOSS OF GENERATOR NO.1 COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
generator	R	penetration
drive shaft	R	sever
accessories connection	R	penetration

L2134 LOSS OF BATTERY COMPONENT LIST

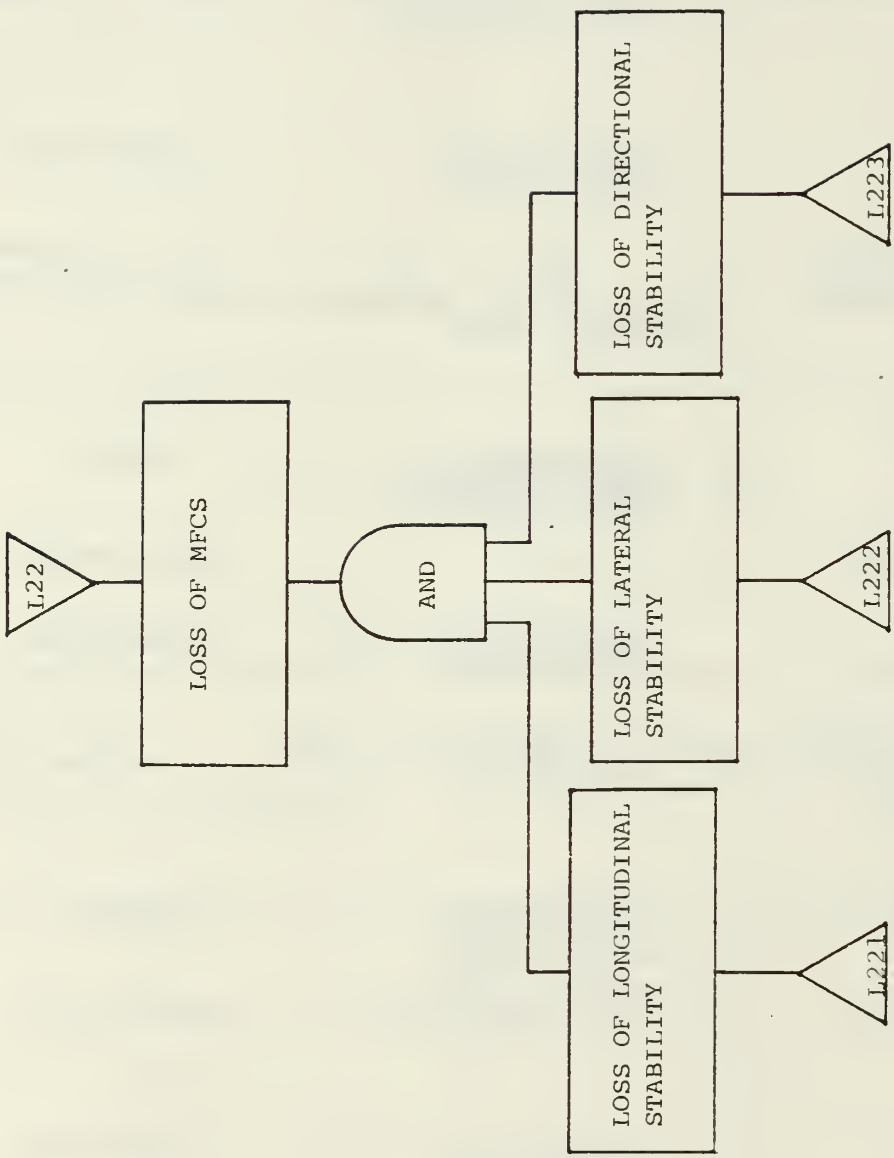
COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
battery	NR	penetration
essential connections	NR	penetration

TABLE 7.4 (cont.) L2135 LOSS OF ESSENTIAL DC BUS NO. 1
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
essential dc bus	R	penetration

L2137 LOSS OF ESSENTIAL AC BUS
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
essential ac bus	NR	penetration



See L221, L222, L223 on next page.

Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) L221 LOSS OF LONGITUDINAL STABILITY
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
push-pull rods	R	sever
rod ends	R	sever
bell cranks and pulleys	R	sever
bearing brackets	R	sever

L222 LOSS OF LATERAL STABILITY
COMPONENT LIST

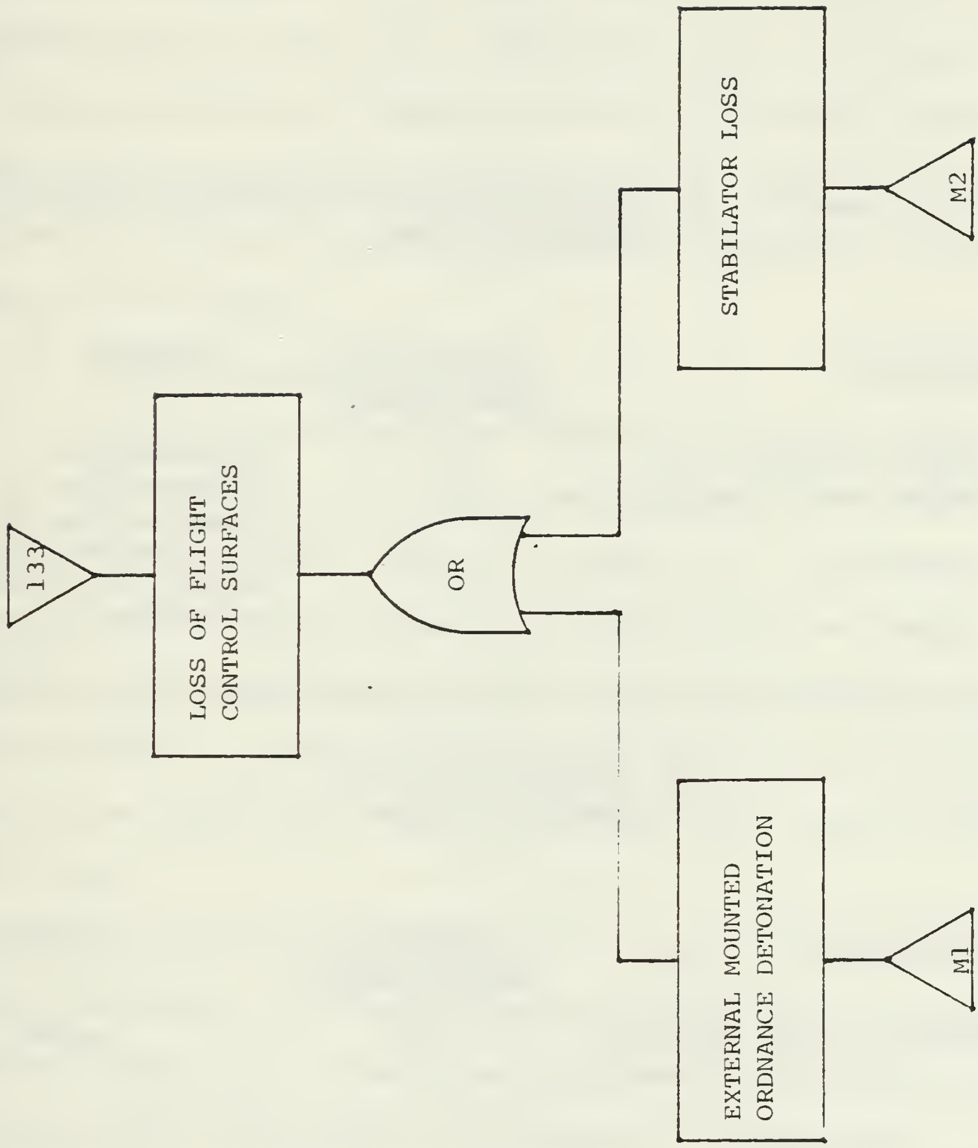
COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
interconnect bungee	NR	jam/sever
push-pull rods	R	jam/sever
rod ends	R	jam/sever
bellcranks and levers	R	jam/sever

L223 LOSS OF DIRECTIONAL STABILITY
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
push-pull rods	R	jam/sever
rod ends	R	jam/sever
bellcranks and levers	R	jam/sever

TABLE 7.4 (cont.) L3 LOSS OF STICK CONTROL
COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
push-pull rods	R	jam/sever
rod ends	R	jam/sever
bellcranks and levers	R	jam/sever
sensor transducer	NR	penetration
control stick	NR	jam/sever
stick grip	NR	jam/sever



See M1 and M2 on next page.

Figure 7.8 (cont.) A-20 Fault Tree Diagram

TABLE 7.4 (cont.) M1 EXTERNAL MOUNTED ORDNANCE DETONATION COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
sidewinder warhead (4)	R	penetration
sidewinder rocket motor (4)	R	penetration penetration of any one of the eight can cause attrition

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M2 STABILATOR LOSS COMPONENT LIST

COMPONENT	REDUNDANCY RELATIONSHIP	DAMAGE
stabilator mounting hinge	NR	sever

4. <u>The Critical Components</u>

Table 7.4 lists the A-20's Critical Components by name, redundancy relationship (R--redundant NR--nonredundant), and damage or kill mode. These kill modes are representative of the ones that Ball [Ref. 2] breaks down by major systems and lists in Table 5.1 on page 145 and then discusses briefly on pages 143-149. The kill modes listed are the most important and most frequently occurring modes of attrition.

5. <u>The Kill Tree</u>

The final set of data obtained from the DMEA is the Kill Tree (also called Fault Tree by MILSTD 2069 [Ref. 1:p. 18]). The Kill Tree, shown in Figure 7.9, introduces the critical components of the A-20 and illustrates their logical redundancy relationships. The Kill Tree is invaluable in that it graphically depicts which components (or subsystems) must be damaged or lost produce the particular kill level.

Nonredundant components are those shown in series. These components, if individually killed, are sufficient to result in the kill. Redundant components are shown in parallel with those which they share an operational redundancy. The word redundant means that the component plus x (x > 1) or more components must be killed to achieve the desired kill level.

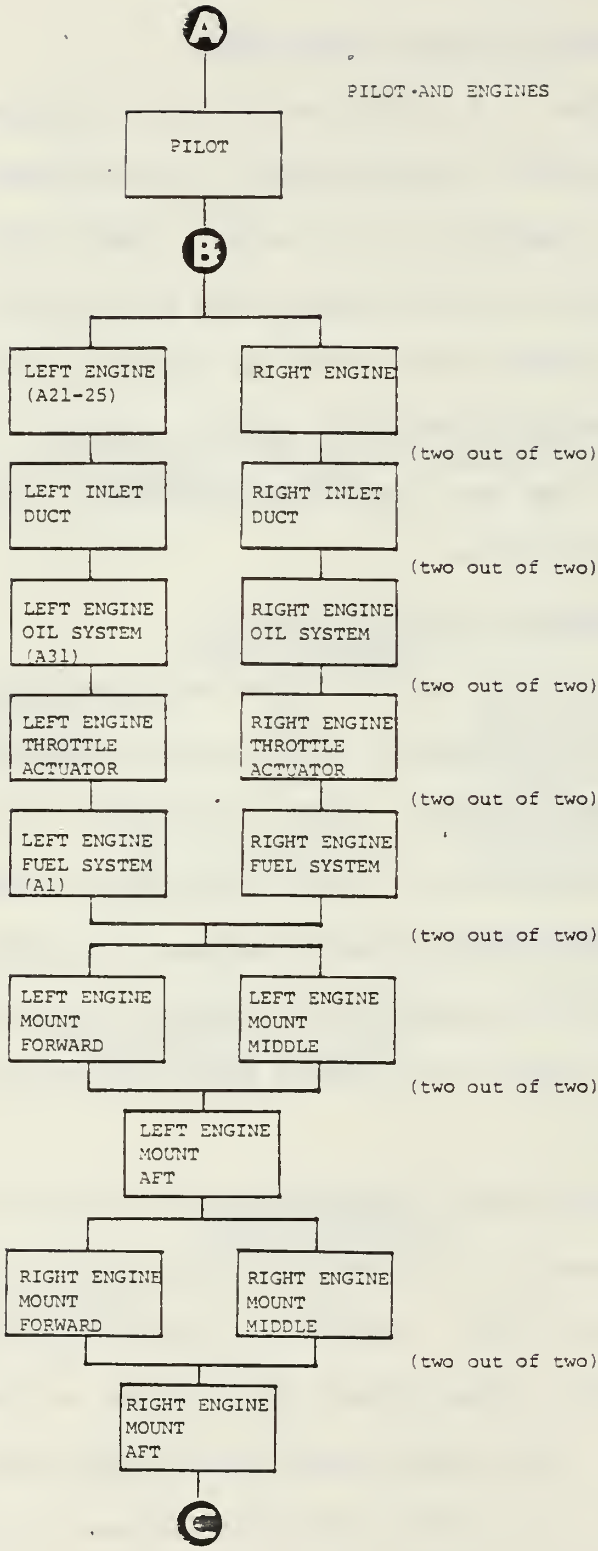

Figure 7.9 A-20 Kill Tree Diagram

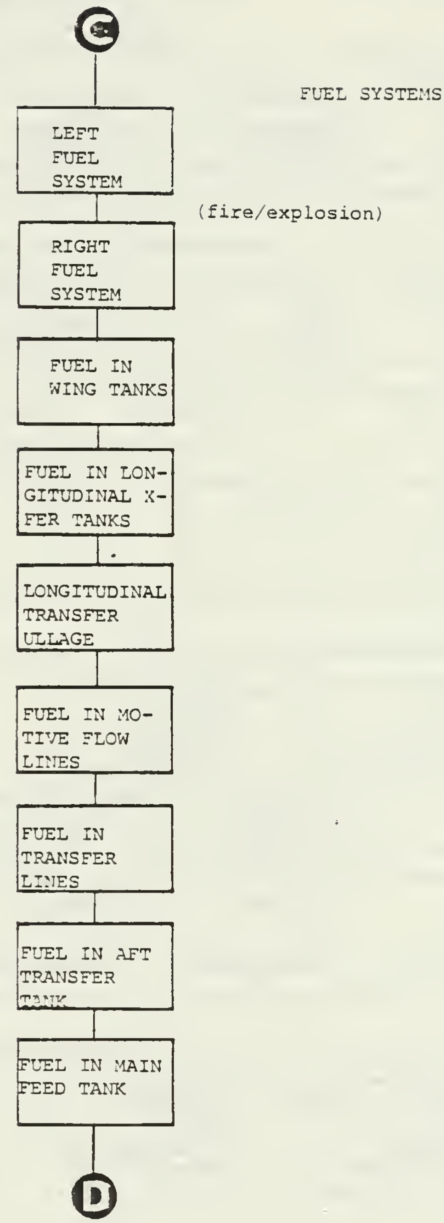

Figure 7.9 (cont.) A-20 Kill Tree Diagram

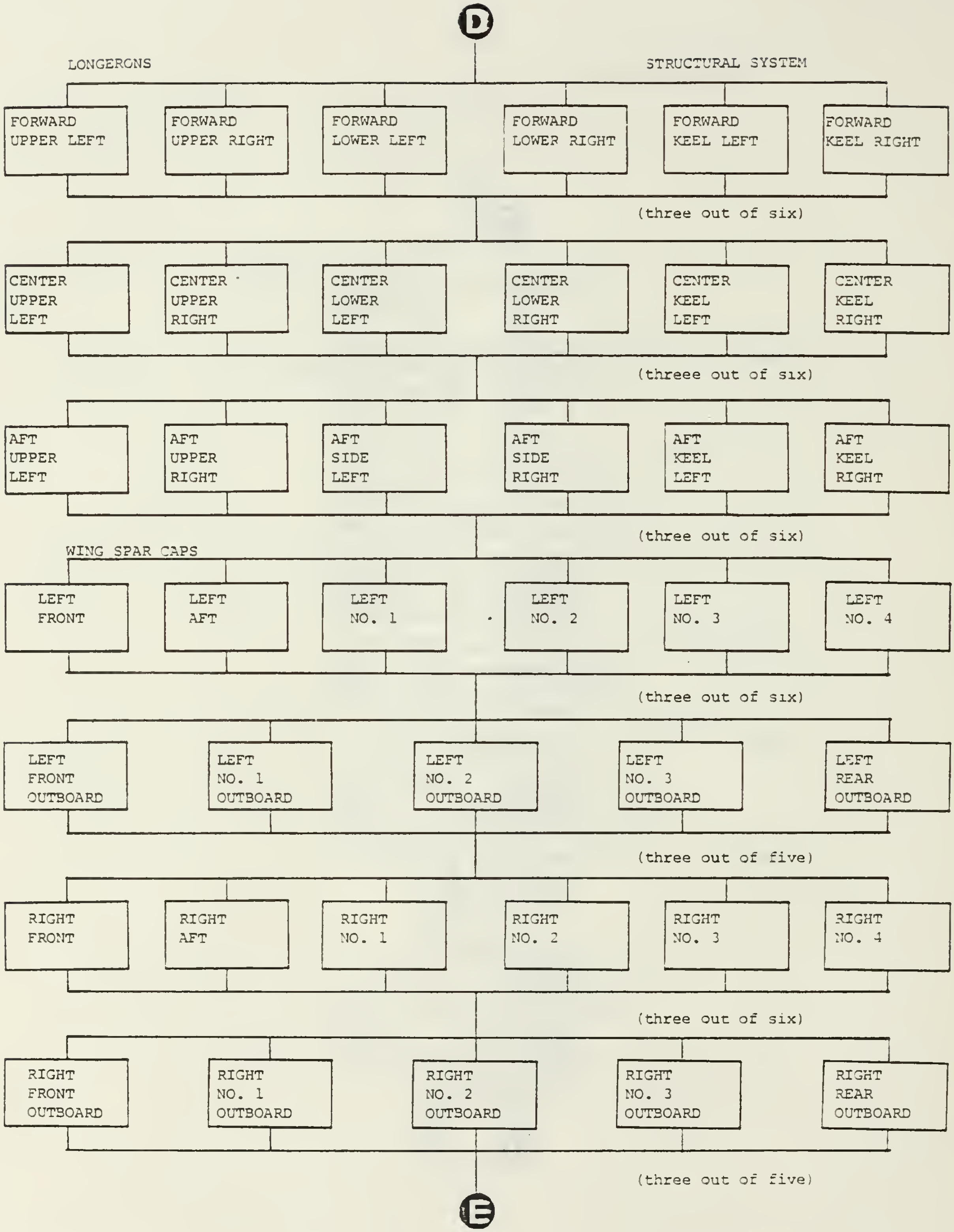

Figure 7.9 (cont.) A-20 Kill Tree Diagram

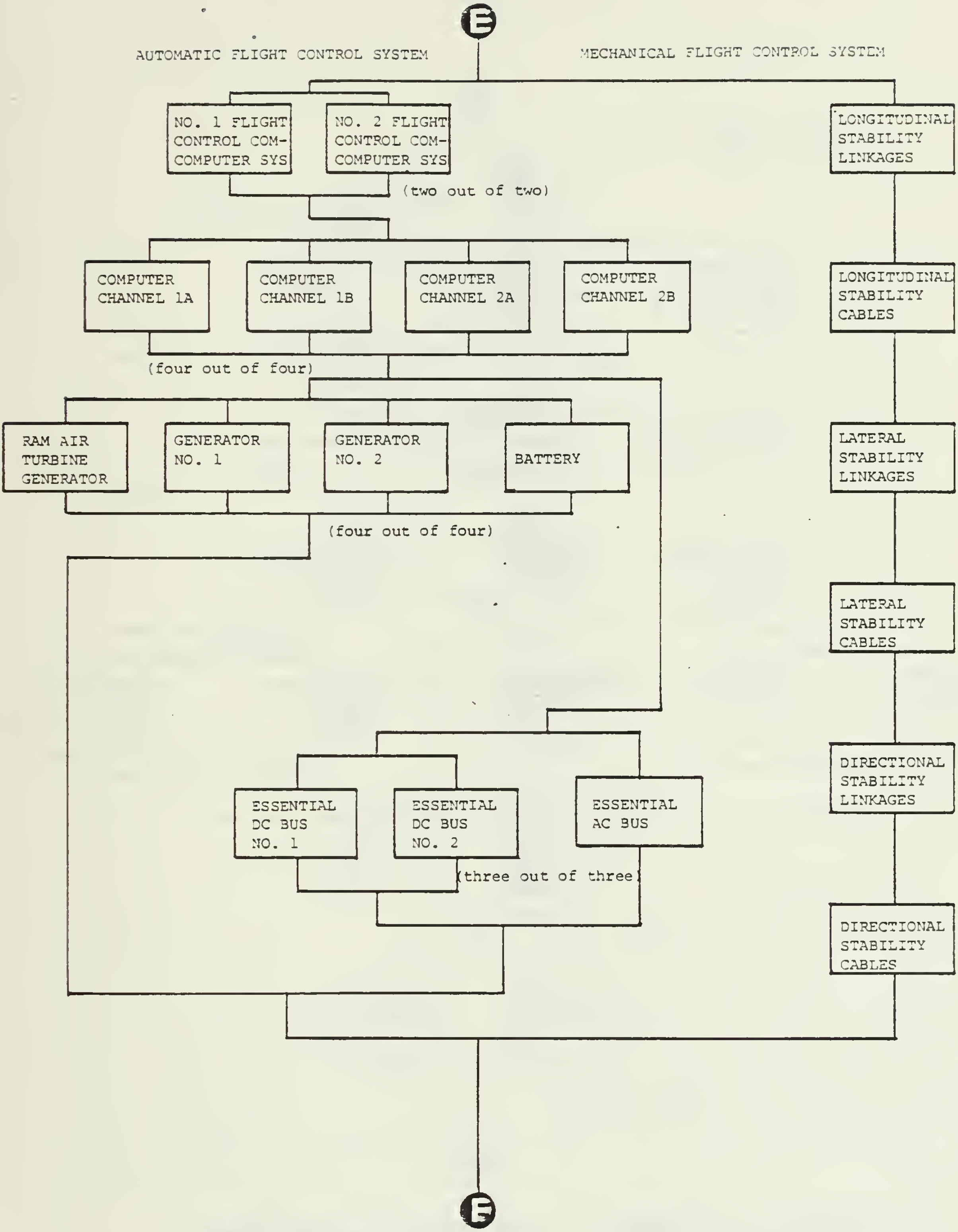

Figure 7.9 (cont.) A-20 Kill Tree Diagram

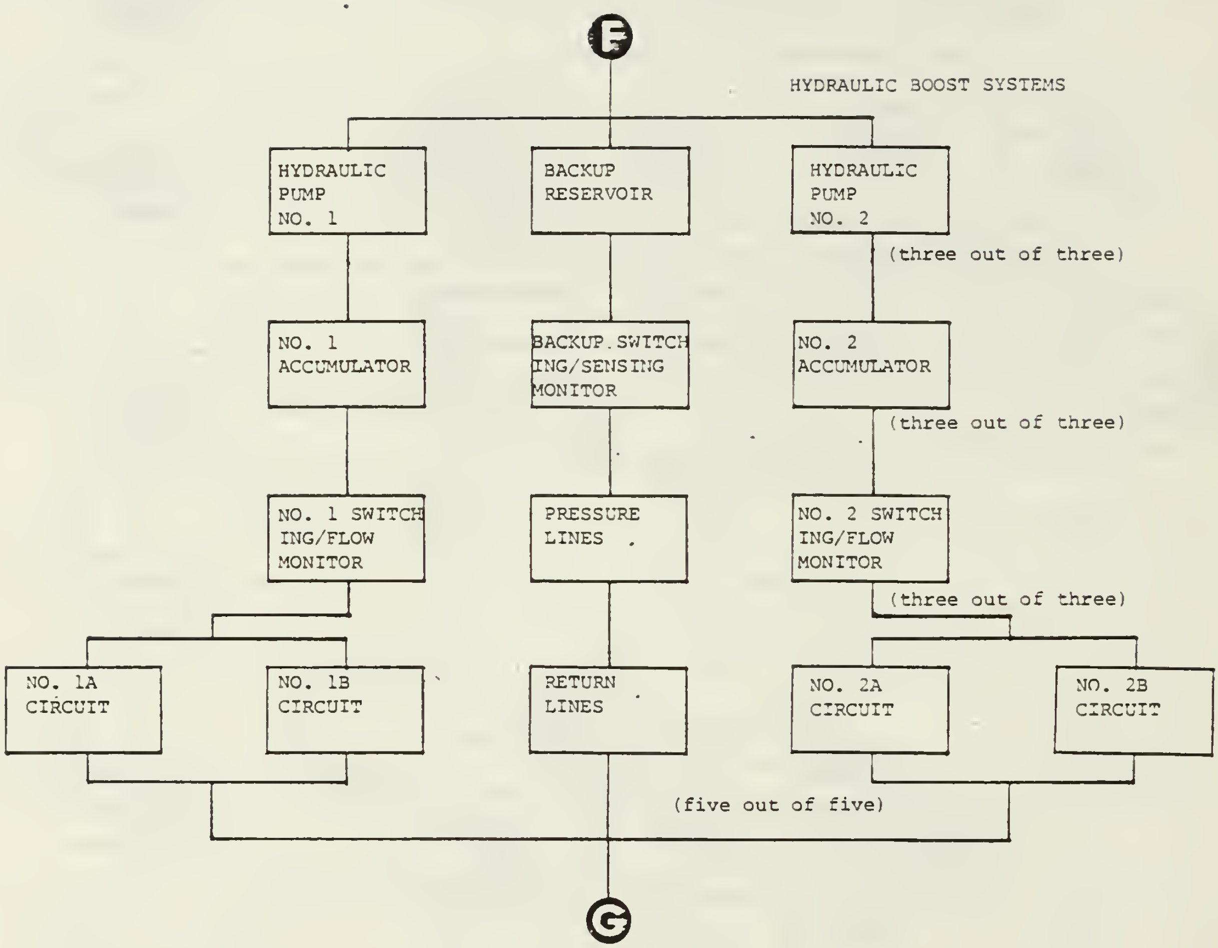

Figure 7.9 (cont.) A-20 Kill Tree Diagram

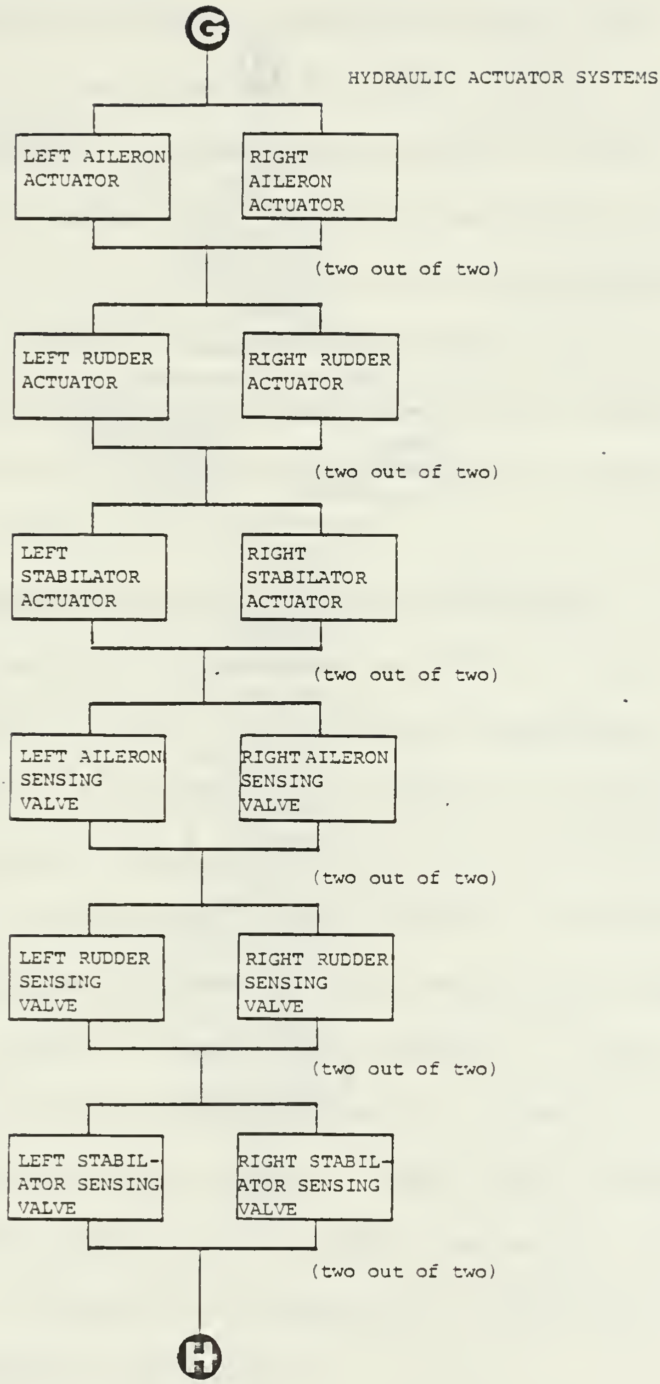

Figure 7.9 (cont.) A-20 Kill Tree Diagram

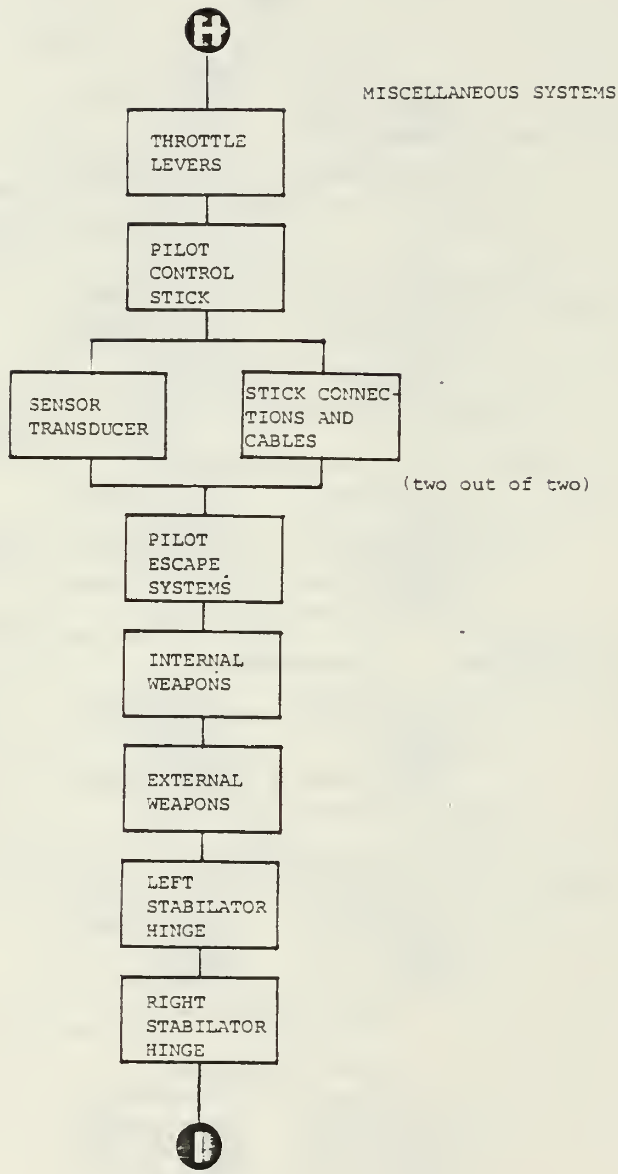

Figure 7.9 (cont.) A-20 Kill Tree Diagram

A complete cut through of the "trunk" of the Kill Tree is required to achieve the A-level attrition kill of the A-20. In portions of the tree where there are redundant relationships (such as the fuel system, the flight control system, the propulsion system or the hydraulics), it is easily seen how this redundancy enhances the survivability of the A-20. The more redundant the systems are, the harder it is to obtain the A-level kill. The values of vulnerability determined in the vulnerability assessment portion of this case study will show this quantitatively.

6. <u>P(k/h) Functions and Critical Components</u>

The culmination of the FMEA and DMEA is the listing of the P(k/h) functions for the critical components. A representative list of the critical components presented in Table 7.4 is given in Table 7.5 This list of critical components is not comprehensive for the whole aircraft. It is made up of selected components from each major subsystem. This was done to enable the reader to more easily grasp the methodology of the assessment, instead of being burdened with trying to assimilate a very long and detailed list. Both redundant and nonredundant components are listed to ensure a thorough vulnerability assessment and treatment of component redundancy.

The probability of kill given a hit functions (P(k/h)) are the first quantitative measures of the

TABLE 7.5 CRITICAL COMPONENT LIST
BY MAJOR SYSTEMS GROUPING

MAJOR SYSTEMS GROUPING	P(k/h) VALUES FOR 100 GRAIN FRAGMENT @ 4000 FPS (uninstalled)
<u>Propulsion Systems Left and Right</u>	
Left Engine	0.3
Right Engine	0.3
Left Inlet Duct	0.5
Right Inlet Duct	0.5
Left Throttle Actuator	0.8
Right Throttle Actuator	0.8
<u>Engine Mounts</u>	
Left Mount Forward	0.3
Right Mount Forward	0.3
Left Mount Aft	0.2
Right Mount Aft	0.2
<u>Pilots Control Inputs</u>	
Left Throttle	0.6
Right Throttle	0.6
Control Stick	0.4
Stick Sensor Transducer	0.5
<u>Hydraulics Systems (No. 1, 2 and Backup)</u>	
Hydraulic Pump No. 1	0.4
Hydraulic Pump No. 2	0.4
Hydraulic Circuit 1A	0.5
Hydraulic Circuit 1B	0.5
Hydraulic Circuit 2A	0.5
Hydraulic Circuit 2B	0.5
No. 1 Accumulator	0.7
Backup Reservoir	0.6
Backup Switching/Sensing Monitor	0.4
Left Aileron Actuator	0.35

TABLE 7.5 (cont.) CRITICAL COMPONENT LIST BY MAJOR SYSTEMS GROUPING

MAJOR SYSTEMS GROUPING	P(k/h) VALUES FOR 100 GRAIN FRAGMENT @ 4000 FPS (uninstalled)
<u>Hydraulics Systems (No. 1, 2 and Backup-cont.)</u>	
Right Rudder Actuator	0.35
Left Stabilator Actuator	0.35
Right Stabilator Actuator	0.35
Left Aileron Sensing Valve	0.6
Right Rudder Sensing Valve	0.5
Right Stabilator Sensing Valve	0.45
<u>Fuel System Fire/Explosion</u>	
Left Fuel System Ullage	0.3
Fuel in Motive Flow Lines	0.8
Fuel in Wing Tanks	0.4
Fuel in Forward Feed Tank	0.2
Fuel in Aft Transfer Tank	0.25
Wing Tank Ullage	0.75
Longitudinal Transfer Tank Ullage	0.65
<u>Flight Controls--Electrical</u>	
AFCS No. 1 (gyro stabilizer, accelerometer, rate/motion sensor)	0.3
AFCS No. 2 (gyro stabilizer, accelerometer, rate/motion sensor)	0.3
AFCS Channel 1A	0.5
AFCS Channel 1B	0.5
AFCS Channel 2A	0.5
AFCS Channel 2B	0.5
Generator No. 1	0.2
Battery	0.3
Essential DC Bus No. 1	0.45
Essential AC Bus	0.4

TABLE 7.5 (cont.) CRITICAL COMPONENT LIST
BY MAJOR SYSTEMS GROUPING

MAJOR SYSTEMS GROUPING	P(k/h) VALUES FOR 100 GRAIN FRAGMENT @ 4000 FPS (uninstalled)
<u>Flight Controls Mechanical</u>	
Longitudinal Stability Cables	0.5
Directional Stability Linkages	0.3
Lateral Stability Cables	0.4
<u>Structure</u>	
Middle Canopy Frame Support	0.25
Forward Longerons	0.15
Aft Longerons	0.10
Left Wing inboard Spar Caps	0.2
Right Wing Outboard Spar Caps	0.2
<u>Crew Member</u>	
Pilot	1.0
<u>Armament/Weapons System</u>	
Missile Motor	0.8
Missile Warhead	1.0
Cannon Ammo Drum	0.6

aircraft's survivability. They are a measure of the probability of component kill when impacted by a fragment. Normally, the P(k/h) functions are listed as a 2-axis graph (see Figure 3.7), relating the damage mechanism's size and velocity at impact. For example (from Figure 3.7), the P(k/h) value for a 120 grain fragment travelling at 4000 feet per second is 0.62. This method of analysis involves many man-hours at test facilities for ballistic testing of the projectile and resultant component damage. The P(k/h) values determined from these functions are computed for the uninstalled component and are employed for all attack directions and impacts anywhere on the component.

For this case study the presentation of assessment methodology is the goal. For this reason, the list of critical components has a respective P(k/h) value, not function, assigned to each component. These values are for generic components and are not based on any actual aircraft. They are based on the assumption of the uninstalled component being struck by a single fragment at a velocity of 4000 feet per second (fps). These values will be used as the starting point or baseline values in the vulnerability assessment. The location of the component inside the system and the aircraft structure has a definite influence on its ultimate numerical value for probability of kill given a hit. Component and structural shielding reduces the velocity of the damage mechanism

and as such its lethality. This results in a change in the P(k/h) values for the components used in the assessment. This change, and the detailed reasoning behind it, will be described in the vulnerability assessment in the next chapter.

VIII. A-20 VULNERABILITY ASSESSMENT

The vulnerability assessment of the A-20 will be the final survivability program task performed in this case study. The methodology for this assessment is found in Chapter 5 of Ball [Ref. 2:pp. 153-221]. Ball presents all the possible techniques and situations for vulnerability assessment, ranging from single hit vulnerability for a non-explosive penetrator or fragment (pages 158-158), to multiple hit vulnerability (pages 169-180), to vulnerability to internally and externally detonating warheads (pages 183-191).

This assessment of the A-20 will determine the aircraft's vulnerability to a single fragment. The damage mechanism used is the 100 grain fragment from the SA-X, the same one that the uninstalled P(k/h) values are based on. The methodology used for the single hit vulnerability is essentially the same as that used by the computer programs FASTGEN and COVART [Ref. 2:pp. 192-195]. In these programs, the single hit vulnerable area of the aircraft and it's components can be assessed from 26 different aspects (Figure 8.1). For the A-20 assessment, the 45 degree azimuth and 45 degree elevation aspect (Figure 8.2) will be used to show the methodology involved in obtaining numerical values for the single hit vulnerability of the A-20.

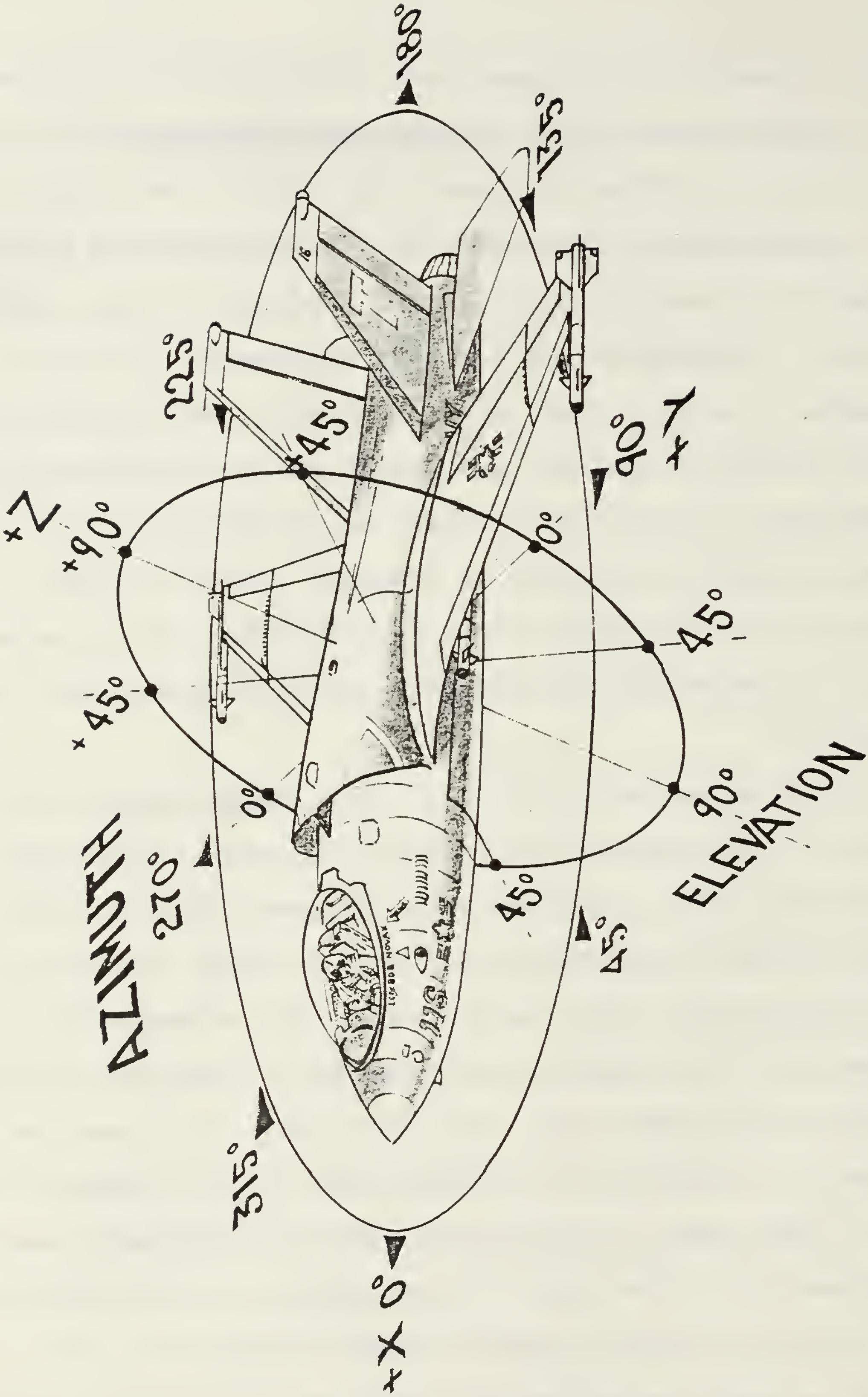

Figure 8.1 The Aircraft Assessment Aspects

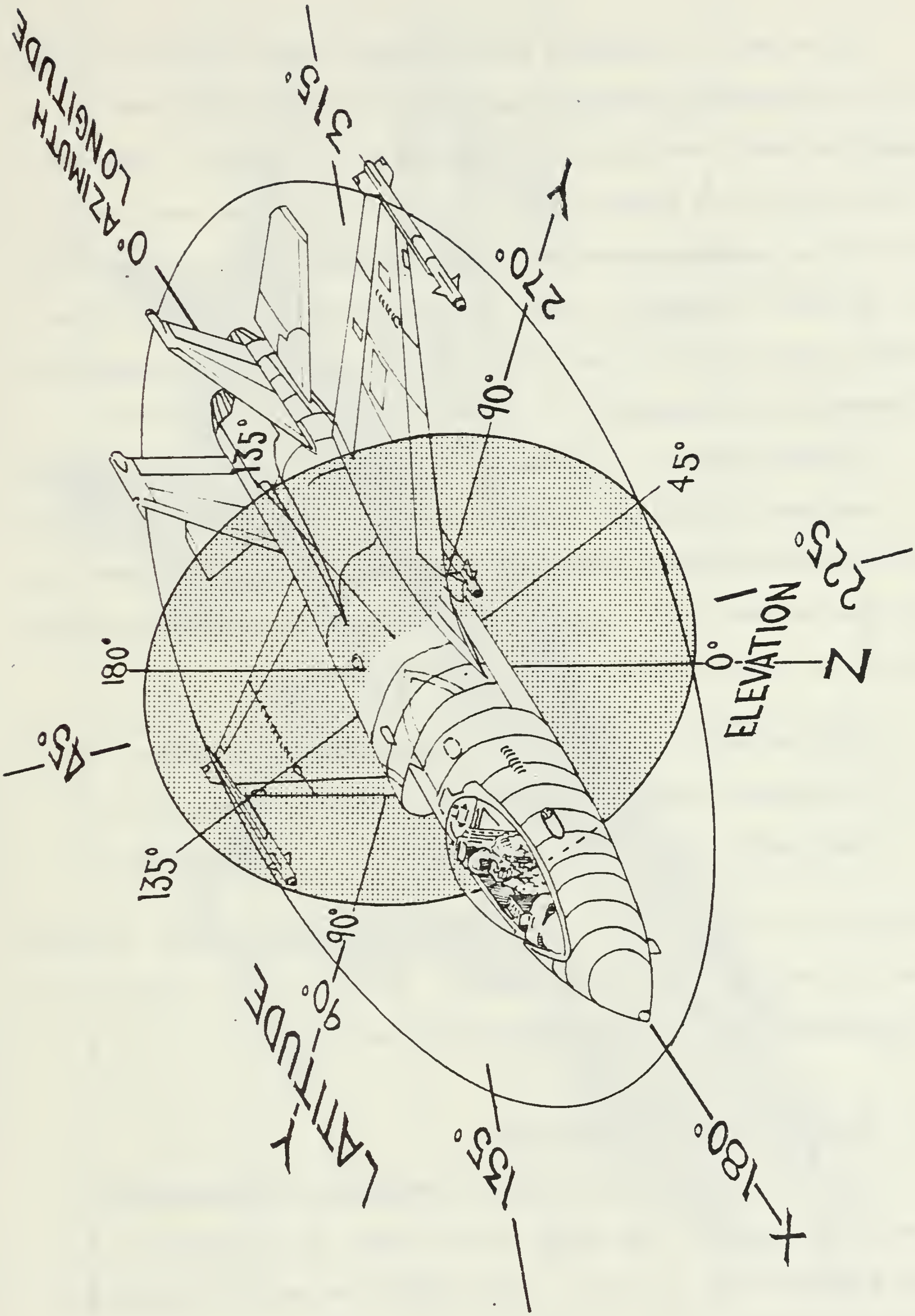

Figure 8.2 A-20 Assessment Aspect

In order to simulate the FASTGEN/COVART computer analysis, a grid with sections measuring 5 feet by 5 feet is superimposed over the A-20 (Figure 8.3). Each 5 foot by 5 foot section is subdivided into 25 one square foot cells to provide a uniform grid cell area to work from. A shotline is randomly located in each of the one square foot cells. These shotlines will be followed as they travel completely through the aircraft.

For the sake of simplicity, just three shotlines will be examined in detail (Figure 8.3). These shotlines illustrate the different types of component situations that may be encountered when doing a single hit vulnerability assessment on an aircraft. These situations are:

1. Nonredundant components with overlap. (shotline 1)
2. Redundant components with no overlap. (shotline 2)
3. Redundant components with overlap. (shotline 3)

Figures 8.4 through 8.9 show the shotlines passing through the various critical components. Table 8.1 is the list of components that lie on each shotline.

A. VULNERABILITY CALCULATIONS

For each shotline situation assessed, the component presented area is the area of one cell in the grid, i.e. one square foot (1 ft.^{2}). The P(k/h) values of the components will be affected by their location within the

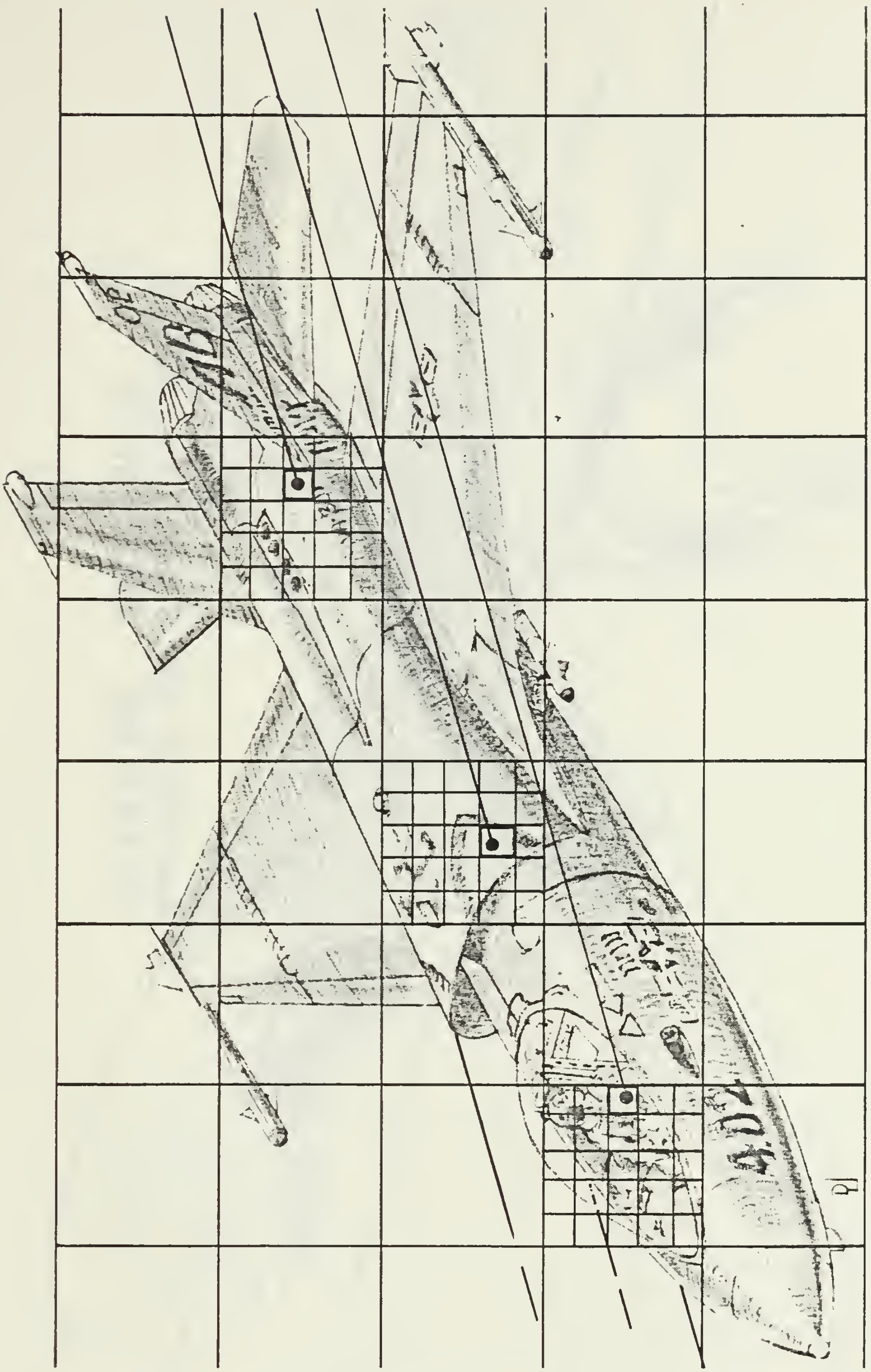

Figure 8.3 A-20 Shotline Grid

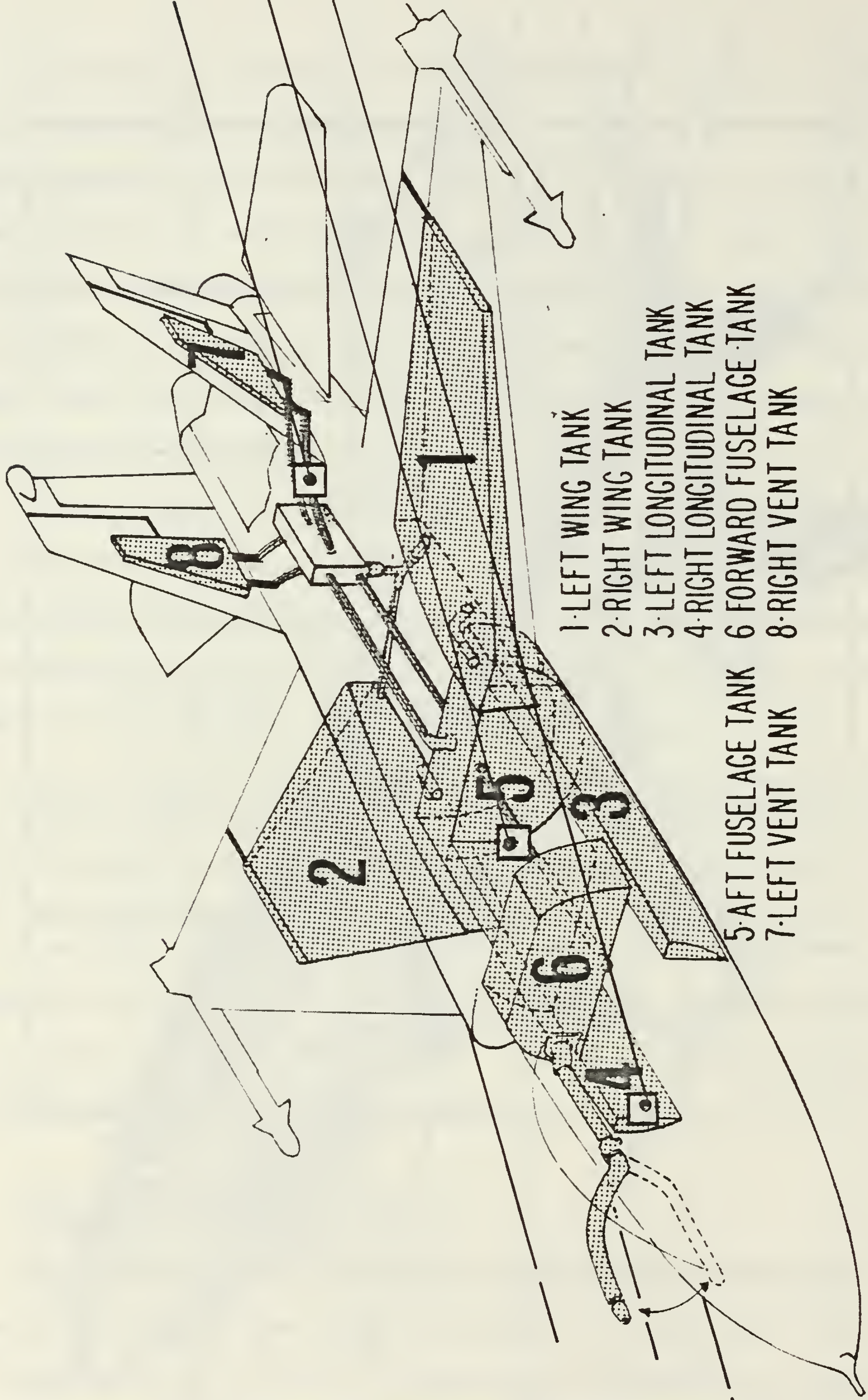

Figure 8.4 Fuel System Shotline Intercepts

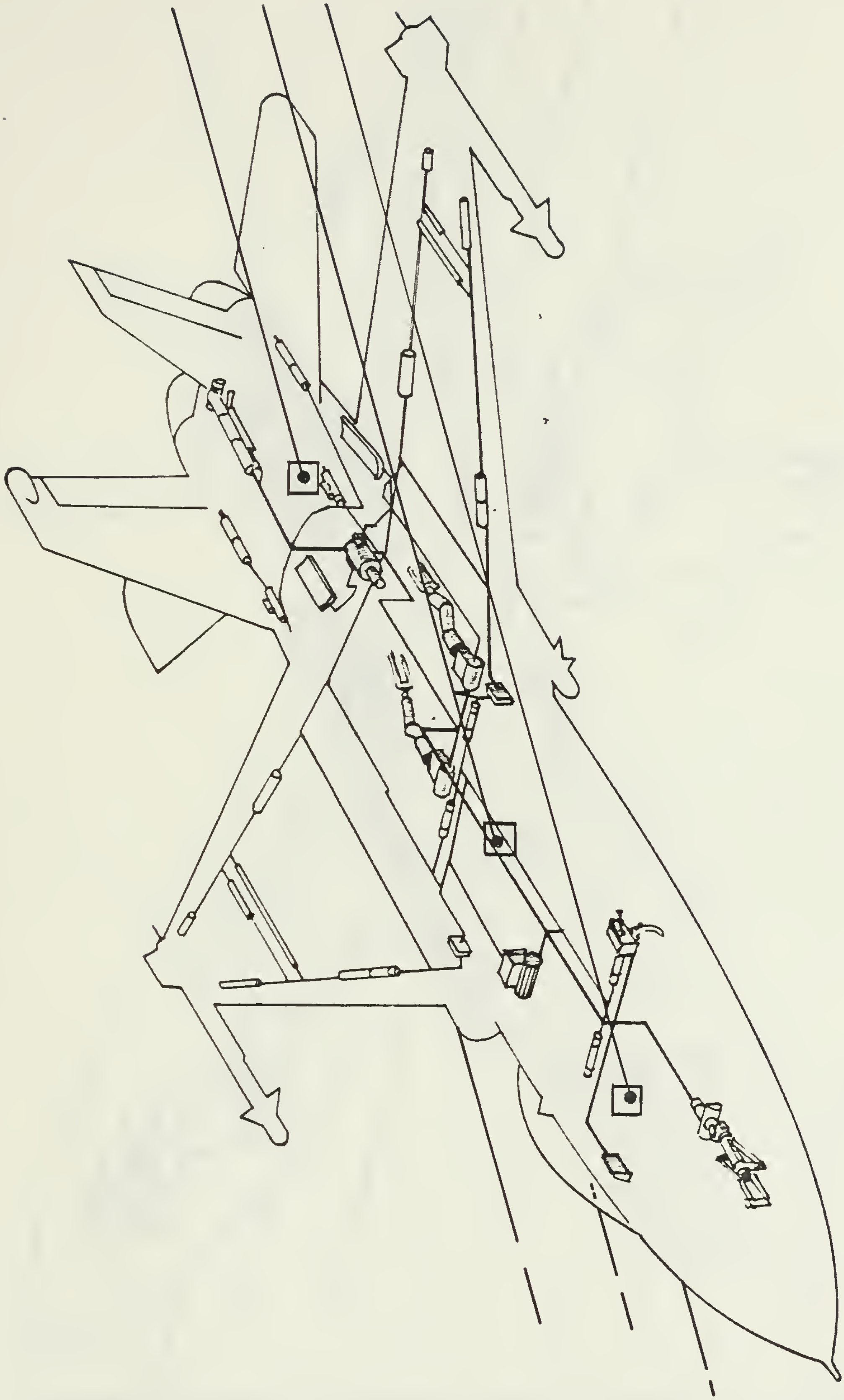

Figure 8.5 Hydraulic System Shotline Intercepts

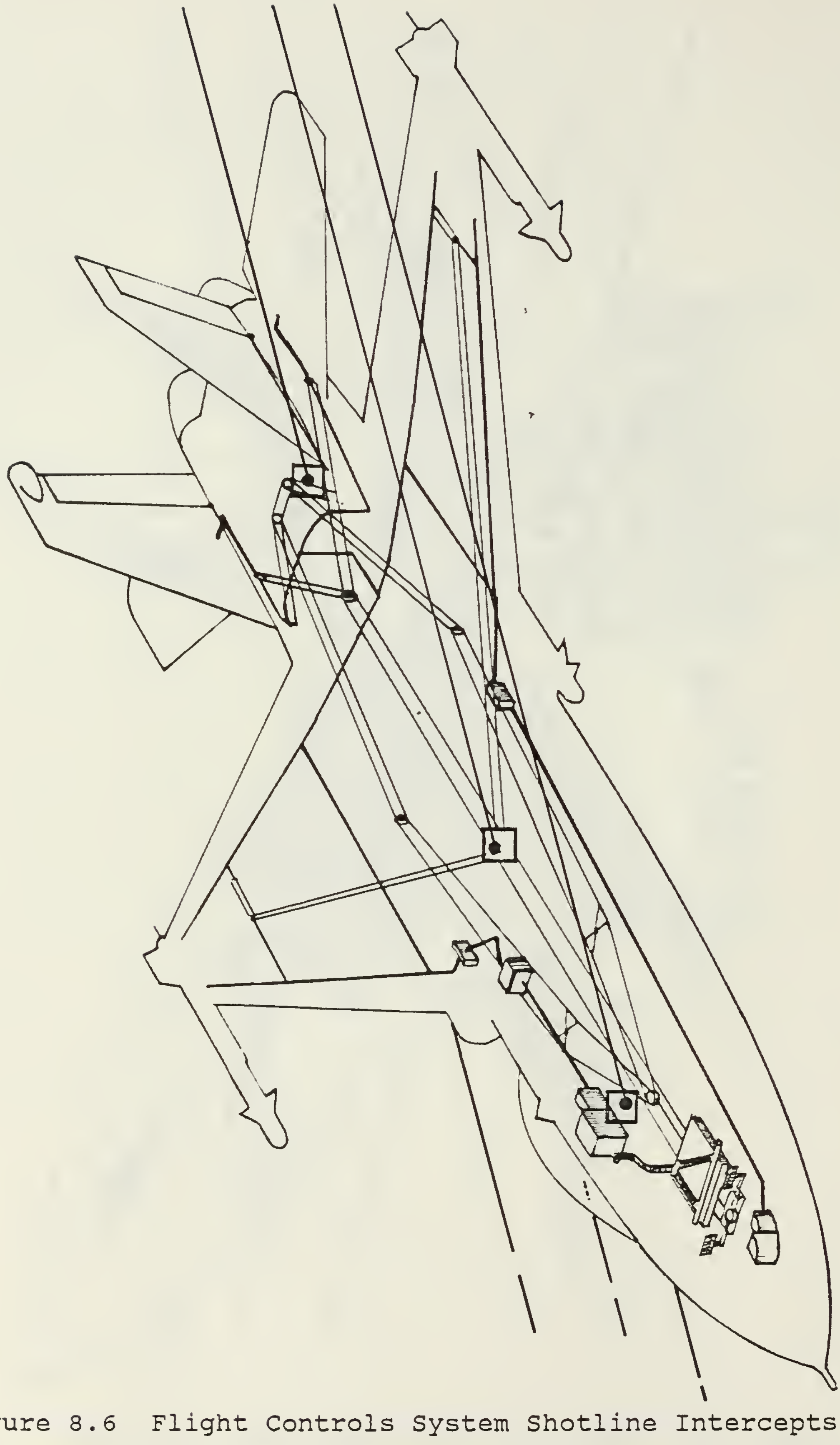

Figure 8.6 Flight Controls System Shotline Intercepts

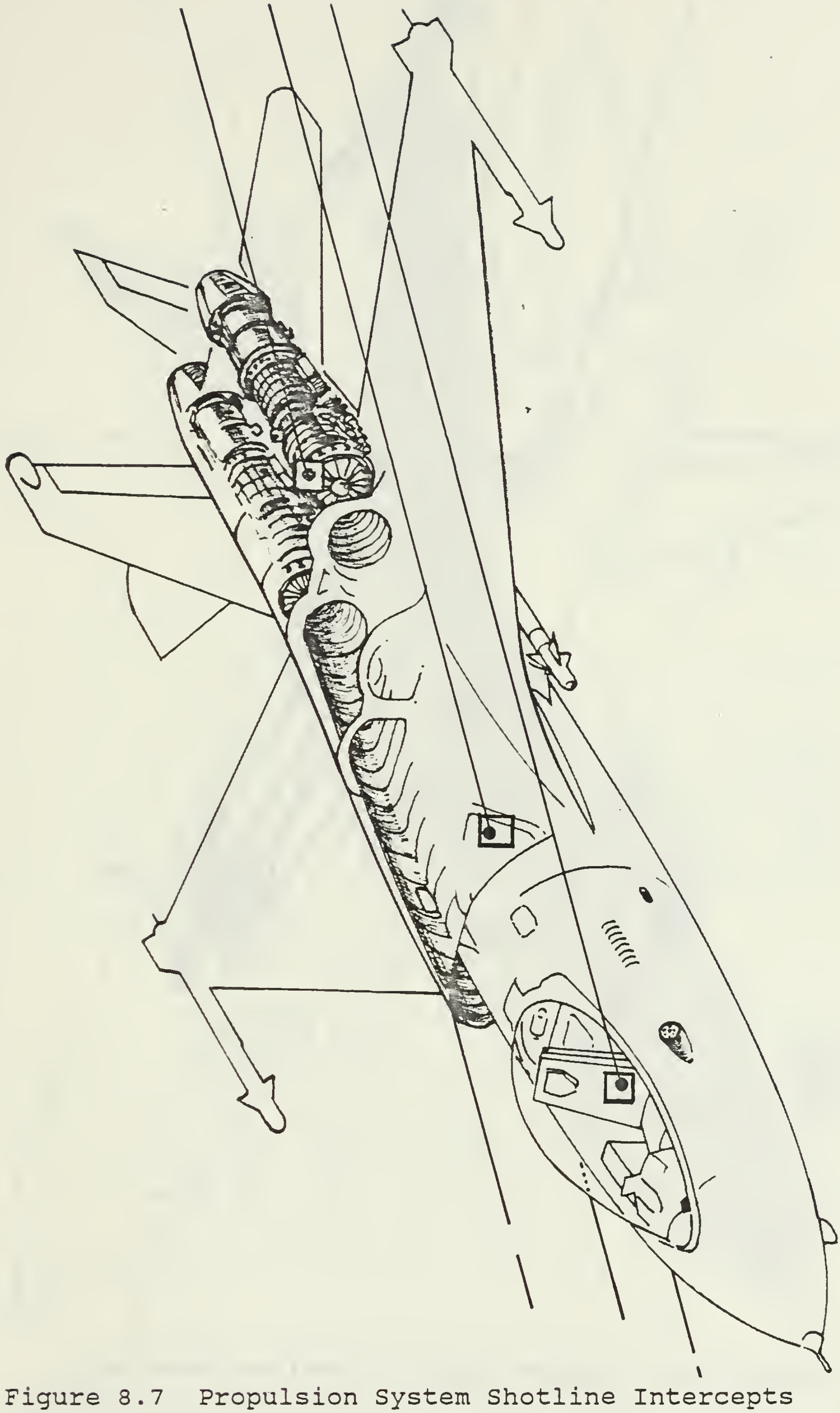

Figure 8.7 Propulsion System Shotline Intercepts

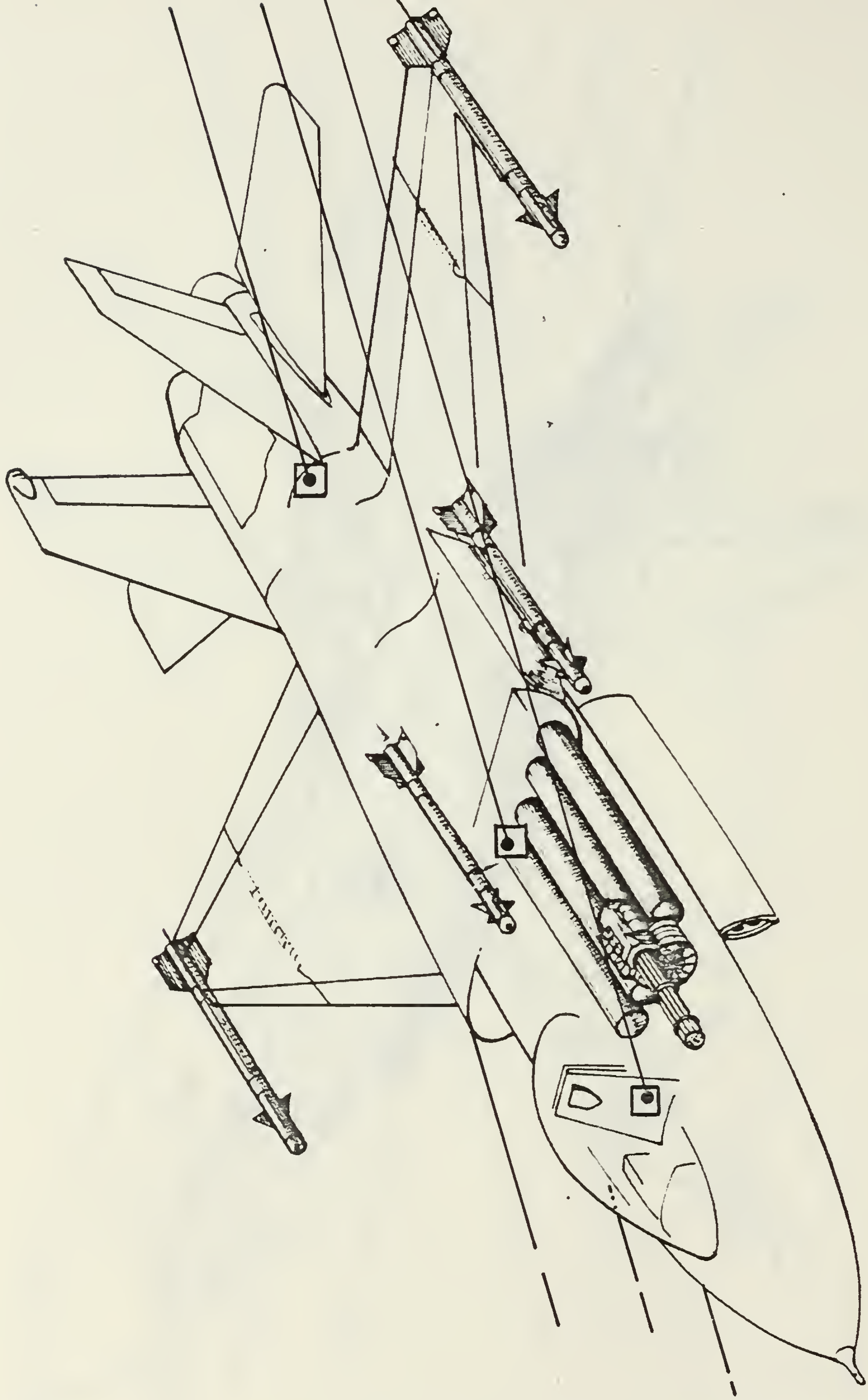

Figure 8.8 Armament System Shotline Intercepts

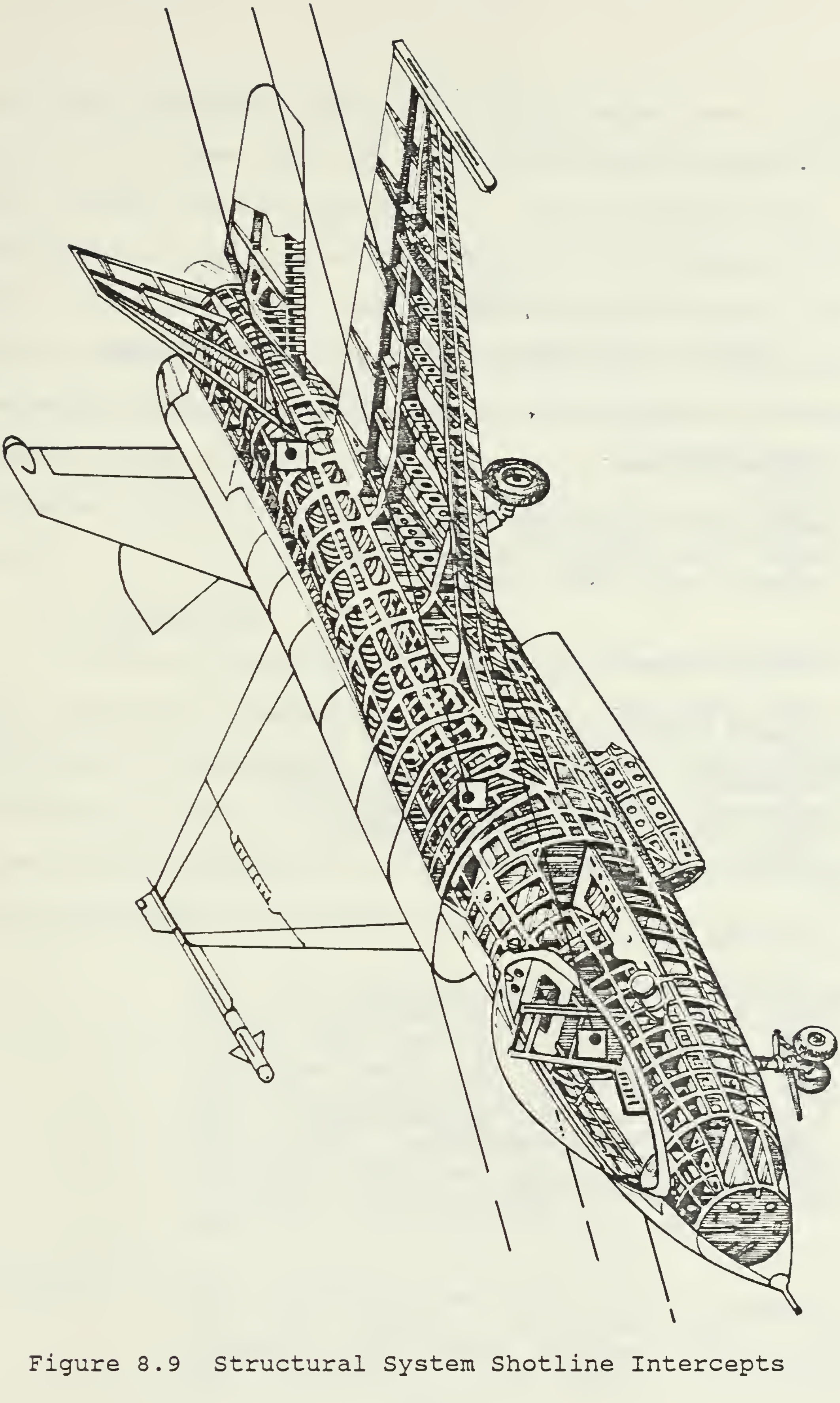

Figure 8.9 Structural System Shotline Intercepts

TABLE 8.1

CRITICAL COMPONENTS INTERSECTED BY SHOTLINES

Shotline No. 1

1. Pilot
2. Mechanical Stabilator Linkage
3. Right Longitudinal Transfer Tank
4. Forward Keel Right Longeron

Shotline No. 2

1. Left Inlet Duct
2. Forward Feed Tank
3. Hydraulic Feed Line Circuit No. 1
4. Mechanical Aileron Linkage Mechanism
5. Outboard Starboard Missile Motor
6. Right Longitudinal Transfer Tank
7. Center Keel Right Longeron

Shotline No. 3

1. Aft Side Left Longeron
2. Left Rudder Hydraulic Actuator
3. Left Engine
4. Left Fuel Vent Line
5. Accessories Section
6. Left Fuel System Motive Flow Line
7. Mechanical Rudder Linkage
8. Right Engine
9. Aft Keel Right Longeron

aircraft. As will be seen, the P(k/h) values used in the analysis are less than the uninstalled values presented in the previous chapter (Table 7.5). This is because the lethality of each fragment is based on its striking velocity on the component. Due to shielding and overlap, the degree of lethality is inversely proportional to the distance the fragment travels through the aircraft. In other words, as the fragment slows down, the resultant P(k/h) value for a hit component is less than its uninstalled value.

1. <u>Definitions</u>

The following definitions parallel Ball's [Ref. 2:pp. 158-159] explanation of the variables used in a vulnerability assessment. In this assessment, everything is related to the cell presented area, whereas Ball presents the methodology based on component presented area. The explanations given below refine Ball's notation.

ci: This subscript represents the "ith" component on the "cth" shotline. In this case study, "c" will have the value of 1, 2 or 3, depending on the particular cell or shotline being analyzed. Shotline/cell 1 (1i) is the forward shotline (entry thru the cockpit--see Figure 8.3). Shotline/cell 2 (2i) is the the middle shotline (entry thru the left inlet duct). Shotline/cell 3 (3i) is the aft shotline (entry thru the left engine).

$A\langle v_{ci}\rangle$: The vulnerable area of the "ith" component on the "cth" shotline. The number that "i" represents is the number assigned to the component in Table 8.1. For example, from Table

8.1, the mechanical stabilator hinge is intersected by shotline 1. The vulnerable area of the hinge is defined by the symbology $A<v_{12}>$.

$A<p_c>$ and: $A<P_c>$ — The presented area of each cell. As mentioned earlier, this value is a constant at 1.0 square feet.

$P<s/h_{ci}>$: — The probability of the "ith" component on the "cth" shotline surviving, given a hit on this component.

$P<k/h_{ci}>$: — The probability of the "ith" component on the "cth" shotline being killed given a hit on this component. These values are also known as the installed $P<k/h>$ values.

$P<S/H_c>$: — The probability of the aircraft surviving given a hit on the "cth" cell.

$P<K/H_c>$: — The probability of the aircraft being killed given a hit on the "cth" cell.

$A<V_c>$: — The vulnerable area of the "cth" cell.

$A<P>$: — The presented area of the entire aircraft. Using Figure 8.2 this was determined to be 399.0 square feet.

$P<S/H>$: — The aircraft probability of survival given a random hit on the aircraft.

$P<K/H>$: — The aircraft probability of kill given a random hit on the aircraft.

$A<V>$: — The total single hit vulnerable area of the aircraft, relative to the presented aspect.

2. Mathematical Relationships

The following mathematical relationships will be used to determine the single hit vulnerability of the A-20. Ball [Ref. 2], presents these relationships on pages 159-169. For "n" components along a shotline and "N" cells on the aircraft:

$$P\langle S/H_c\rangle = (P\langle s/h_{c1}\rangle)(P\langle s/h_{c2}\rangle)\ .\ .\ .\ (\langle Ps/h_{cn}\rangle) \qquad (8.1)$$

$$P\langle s/h_{ci}\rangle = 1 - P\langle k/h_{ci}\rangle \qquad (8.2)$$

$$A\langle v_{ci}\rangle = (P\langle k/h_{ci}\rangle)(A\langle p_c\rangle) \qquad (8.3)$$

$$P\langle K/H_c\rangle = 1 - P\langle S/H_c\rangle \qquad (8.4)$$

$$A\langle V_c\rangle = (P\langle K/H_c\rangle)(A\langle P_c\rangle) \qquad (8.5)$$

$$A\langle V\rangle = A\langle V_1\rangle + A\langle V_2\rangle + .\ .\ . + A\langle V_N\rangle \qquad (8.6)$$

$$P\langle K/H\rangle = A\langle V\rangle/A\langle P\rangle \qquad (8.7)$$

$$P\langle S/H\rangle = 1 - P\langle K/H\rangle \qquad (8.8)$$

3. Nonredundant Components with Overlap (shotline 1)

This first situation is specifically addressed by Ball [Ref. 2:pp. 163-166]. The components intersected by shotline 1 will be used to show the methodology for this situation. The results of the analysis on this shotline will be values for $P\langle K/H_1\rangle$ and $A\langle V_1\rangle$.

The list of components that are intersected by shotline 1 are given in Table 8.1 and are also listed in Table 8.2. The uninstalled $P<k/h>$ values for each of these components ($P<k/h_{un}>$), is given in Table 7.5 and is also given in Table 8.2. The $P<k/h>$ value for the installed components ($P<k/h_{ci}>$) has been estimated and is presented in Table 8.2. The component vulnerable are in each cell ($A<v_{ci}>$) is equal to the $P<k/h_{ci}>$ value because of the fact that each cell's presented area ($A<p_c>$ is equal to one square foot. This will be true for all three situations.

TABLE 8.2 SHOTLINE 1
NONREDUNDANT COMPONENTS WITH OVERLAP

Component	$P<k/h_{un}>$	$P<k/h_{ci}>$ & $A<v_{ci}>$[1]
1. pilot	1.0	0.9
2. mechanical stabilator hinge	0.3	0.2
3. right longitudinal transfer tank	0.65	0.3
4. forward keel right longeron	0.15	0.10

[1] $A<v_{ci}>$ is in square feet

For this situation, the mathematics will be presented in detail, showing equations, value substitutions, and methodology. The other two situations will be presented by citing appropriate equations and values. The only portions that will be examined in detail in the other two situations are those that make each one unique.

To determine the vulnerability measures of the aircraft given a hit on cell 1, the following methodology is followed:

Using Eqns. (8.1) and (8.2) and the data given in Table 8.2, the value for $P\langle S/H_1\rangle$ is determined from

$$P\langle S/H_1\rangle = (1 - P\langle k/h_{11}\rangle)(1 - P\langle k/h_{12}\rangle)(1 - P\langle k/h_{13}\rangle)(1 - P\langle k/h_{14}\rangle).$$

Substituting the values for $P\langle k/h_{1i}\rangle$ from Table 8.2 into the expression for $P\langle S/H_1\rangle$ gives

$$P\langle S/H_1\rangle = (1 - 0.9)(1 - 0.2)(1 - 0.3)(1 - 0.1)$$
$$= 0.050.$$

Using Eqn. (8.4) to determine the probability of killing the aircraft given a hit on cell 1 gives

$$P\langle K/H_1\rangle = 1 - P\langle S/H_1\rangle$$
$$= 1 - 0.050$$
$$= 0.950.$$

Equation (8.5) is used to determine the vulnerable area of cell 1. This value will be used later to determine the A<V> of the aircraft and the P<K/H> of the aircraft. According to Eqn. (8.5)

$$
\begin{aligned}
A<V_1> &= (P<K/H_1>)(A<P_1>) \\
&= (0.950)(1.0\ \text{ft.}^2) \\
&= 0.950\ \text{ft.}^2
\end{aligned}
$$

The only difference between the A-20 assessment given here and Ball's approach is that Ball [Ref. 2] uses the total presented area of the component to determine the component vulnerable area. However, this procedure (which is equivalent to the computerized procedure) treats each cell as a unique "component". Eventually, the total vulnerable area of each component is computed as the sum of the component vulnerable areas on each cell.

This first situation resulted in a high value for the $P<K/H_1>$. This value reflects the lack of component redun- dancy in this part of the aircraft. The next situation, redundant components with no overlap, shows how redundancy can reduce the $P<K/H_c>$ value.

4. <u>Redundant Components with No Overlap (shotline 2)</u>

This second situation is addressed by Ball [Ref. 2:pp. 166-168]. Table 8.3 presents the components intersected by shotline 2 and their uninstalled P<k/h> values.

TABLE 8.3 SHOTLINE 2
REDUNDANT COMPONENTS WITH NO OVERLAP

Component	$P<k/h_{un}>$	$P<k/h_{ci}>$ & $A<v_{ci}>$[1]
1. left inlet duct	0.5	0.4
2. forward feed tank (fire/explosion)	0.2	0.15
2a. cascade effect--forward feed tank penetration result: hydraulic ram and left engine kill	---	0.25
3. hydraulic feed line circuit no. 1 (Redundant)	0.5	0.3
4. mechanical aileron linkage mechanism	0.3	0.1
5. outboard starboard missile motor	0.8	0.5
6. right longitudinal transfer tank	0.65	0.20]
7. center keel right longeron (Redundant)	0.15	0.05

[1]$A<v_{ci}>$ is in square feet.

These components will be used to assess the effect of redundancy in components and also to show the effect of cascading damage [Ref.2: pp. 165-166]. Component redundancy has a significant effect on the values of $P<S/H_2>$ and $A<V_2>$. A single hit on the cell will not kill enough of the redundant components to cause a kill of the aircraft. (The theory and logic behind this statement is

shown by Ball on pages 167-168, Eqns. (5.22a-d). This results in the redundant components not being a factor in the calculations for the aircraft's vulnerability measures.

Cascading damage also has a significant effect on the aircraft's vulnerability. This is a type of damage to a component not actually hit by the damage mechanism but that is damaged due to the response of the hit component. This damage may or may not be severe enough to cause a loss of the aircraft. This cascading effect will be illustrated by examining the consequences of the hit on the forward feed tank, component 3.

The cascading effect of forward feed tank's damage essentially "creates" another critical component. In this situation, the fuel tank can be killed by a fire/explosion with a P<k/h> of 0.15 as shown in Table 8.3. The cascade effect occurs when the fuel tank is hit and hydraulic ram causes it to weaken structurally to the point where fuel leaks from the tank into the left inlet duct and is ingested by the engine. This in turn causes a kill of the engine and hence the aircraft. The probability that this occurs is found to be 0.25 (Table 8.3).

Since the engine is not located along this shotline, $P<k/h_{ci}>$ and $A<v_{ci}>$ values for the "created" component must be determined for this situation using the P<k/h> data and Ball's methodology on pages 163-165. The

aircraft can survive the hit in the fuel tank if there is neither a fire kill or a fuel ingestion kill of the engine. The probability that neither of these will occur is found by utilizing Eqn. (8.2). The product of the probability that there is no fire, (1 - 0.15), and the probability that there is no fuel ingestion kill of the engine, (1 - 0.25), is 0.64. Therefore, the probability of kill of this "created" component considering the cascading effect is (1 - 0.64) = 0.36. Thus, by accounting for the cascading effect of the fuel tank damage a critical component is "created" for this situation whose probability of kill is greater than either of the components that contributed to its creation.

The analysis of this situation will be presented in two parts. The first part will show the effects of the cascading damage on the $P<K/H_2>$, and $A<V_2>$ values. The second part will show how the values change without the cascading damage being a factor.

The values for $P<S/H_2>$, $P<K/H_2>$ and $A<V_2>$ for the redundant and cascading situation are calculated using the same methodology and equations (8.1 thru 8.5) as in the first situation. For the cascading damage problem, only six components (1, 2, 2a, 4, 5 and 6) are used to determine the vulnerability values. As shown in Table 8.3, components 3 and 7 are redundant and do not contribute to the aircraft's single hit vulnerability (Note, however, that

every component, redundant or not, has a vulnerable area as given in Table 8.3).

The computed values for redundancy and cascading damage without overlap are as follows:

$$P<S/H_2> = (1 - 0.4)(1 - 0.15)(1 - 0.25)(1 - 0.1)(1 - 0.5)(1 - 0.2) \qquad \text{see (8.1)}$$

$$= 0.138.$$

(The product of the second and third terms in the above equation equals 0.64. From Eqn. (8.1), (1 - 0.64) equals 0.36, the value of the $P<k/h>$ of the "created" critical component.)

$$P<K/H_2> = 1 - 0.138 \qquad \text{see (8.4)}$$

$$= 0.862.$$

$$A<V_2> = 0.979 \text{ ft.}^2 \qquad \text{see (8.5)}$$

For comparative purposes, the following values were computed as if component redundancy did not exist in the above situation:

$$P<S/H_2> = 0.092. \qquad \text{see (8.1)}$$

$$P<K/H_2> = 0.908. \qquad \text{see (8.4)}$$

$$A<V_2> = 0.908 \text{ ft.}^2 \qquad \text{see (8.5)}$$

From this simple comparative example shown, it can be seen that component redundancy does decrease the probability of aircraft kill given a hit in cell 2.

If cascading damage was not considered in this situation, then the engine kill is not considered and the

third term ((1 - 0.25)) in the expression for $P\langle S/H_2\rangle$ becomes unity. Calculations of the vulnerability values for both the redundant and nonredundant situations (for comparative purposes) follow.

The non-cascading redundant component calculations use only components 1, 2, 4, 5 and 6 (As labeled in Table 8.3).

$P\langle S/H_2\rangle = 0.184.$ see (8.1)

$P\langle K/H_2\rangle = 0.816.$ see (8.4)

$A\langle V_2\rangle = 0.816$ ft.^{2} see (8.5)

The non-cascading nonredundant component calculations use components 1, 2, 3, 4, 5, 6 and 7:

$P\langle S/H_2\rangle = 0.122.$ see (8.1)

$P\langle K/H_2\rangle = 0.878.$ see (8.4)

$A\langle V_2\rangle = 0.878$ ft.^{2} see (8.5)

These analyses show the importance of properly considering cascading damage and component redundancy. By eliminating the cascading damage problem, the survivability of the aircraft if hit in this cell increases significantly ($P\langle S/H_2\rangle$ of 0.184 vice 0.122). This is a design consideration that will be discussed later in this chapter.

5. <u>Redundant Components with Overlap (shotline 3)</u>

The final situation discussed is where redundant, overlapping components occur along the same shotline (shotline 3). Table 8.4 provides the components as intersected by shotline 3. Ball [Ref. 2], addresses this situation on pages 168-169 of his text. Specifically, Eqns. (5.22a) and (5.22b) [Ref. 2:p. 167] show how redundancy and overlap are handled. In this situation, a single hit in the overlap region has the probability of killing both engines.

The calculations that follow exhibit the methodology required for this situation. Comparative values are also computed to show the probabilities if there was no overlap in the region.

The methodology for calculating the vulnerability values is very similar to that displayed in the first two situations. The difference is noticed when accounting for the redundant, overlapping engines. This is handled by applying Ball's Eqn. (5.22b) [Ref. 2:p. 167] to the engines and the author's Eqns. (8.1) and (8.2) as follows:

$$P\langle S/H_3\rangle = (1 - (P\langle k/h_{33}\rangle)(P\langle k/h_{38}\rangle))(1 - P\langle k/h_{34}\rangle)$$
$$(1 - P\langle k/h_{35}\rangle)(1 - P\langle k/h_{36}\rangle)(1 - P\langle k/h_{37}\rangle)$$
$$(1 - P\langle k/h_{32}\rangle).$$

TABLE 8.4 SHOTLINE 3
REDUNDANT COMPONENTS WITH OVERLAP

Component	$P<k/h_{un}>$	$P<k/h_{ci}>$ & $A<v_{ci}>$[1]
1. aft side left longeron (Redundant without Overlap)	0.10	0.07
2. left rudder hydraulic actuator	0.35	0.3
3. left engine (Redundant with Overlap)	0.3	0.25
4. left forward fuel vent line	0.4	0.35
5. accessories section	0.6	0.2
6. left fuel system motive flow line	0.8	0.65
7. mechanical rudder linkage	0.3	0.2
8. right engine (Redundant with Overlap)	0.3	0.15
9. aft keel right longeron (Redundant without Overlap)	0.10	0.01

[1] $A<v_{ci}>$ is in square feet

Note that components 1 and 9 are not included in these calculations because they are redundant (with other components not on the shotline) and do not overlap. The vulnerability values are as follows:

$$P\langle S/H_3\rangle = (1 - (0.25)(0.15))(1 - 0.35)(1 - 0.2)(1 - 0.65)$$
$$(1 - 0.2)(1 - 0.3) \qquad \text{see (8.1)}$$
$$= 0.098.$$

$$P\langle K/H_3\rangle = 1 - 0.098 \qquad \text{see (8.4)}$$
$$= 0.902.$$

$$A\langle V_3\rangle = 0.902 \text{ ft.}^2 \qquad \text{see (8.5)}$$

If the shotline did not not intersect the two redundant, overlapping components, the method of calculation is the same as in the second situation discussed, redundant components without overlap. The comparative calculations are as follows:

$$P\langle S/H_3\rangle = 0.101. \qquad \text{see (8.1)}$$

$$P\langle K/H_3\rangle = 0.898. \qquad \text{see (8.4)}$$

$$A\langle V_3\rangle = 0.898 \text{ ft.}^2 \qquad \text{see (8.5)}$$

With redundancy and no overlap, the aircraft's chances of survival increase from 0.098 to 0.101. The overlap area has a definite detrimental affect on the aircraft survivability from this aspect being assessed.

6. Overall Aircraft Survivability

Equations (8.6), (8.7) and (8.8) provide the mathematical relationships needed to determine the overall vulnerable area and probability of survival.

From the aspect presented in Figure 8.2, the value for N in Eqn.(8.6) is 449 cells. For the sake of brevity, the A<V> of the aircraft was estimated to be

$$
\begin{aligned}
A<V> &= 0.950 \text{ ft.}^2 + 0.979 \text{ ft.}^2 + 0.902 \text{ ft.}^2 + A<V_4> + \\
&\qquad \cdots + A<V_N> \\
&= 300.0 \text{ ft.}^2 \text{ (estimate for methodology)}
\end{aligned}
$$

The P<K/H> is determined from Eqn. (8.7). The aircraft's A<P> = 399.0 square feet.

$$
\begin{aligned}
P<K/H> &= A<V>/A<P> \\
&= 300.0 \text{ ft.}^2/399.0 \text{ ft.}^2 \\
&= 0.752.
\end{aligned}
$$

The P<S/H> of the A-20 is calculated by using Eqn. (8.8):

$$
\begin{aligned}
P<S/H> &= 1 - P<K/H> \\
&= 1 - 0.752 \\
&= 0.248.
\end{aligned}
$$

These values may not seem to be very realistic, nor are they necessarily intended to be. As has been repeatedly stated throughout this case study, all values used are based on the author's desire to present the assessment in a clear, concise and unclassified manner. This case study is meant to show the methodology involved in

conducting a vulnerability assessment, not to determine actual, viable vulnerability values.

B. VULNERABILITY REDUCTION FEATURES

The remainder of this chapter briefly discusses several of the vulnerability reduction features that Ball presents in his text [Ref. 2:pp. 199-221] and how they relate to the A-20 and this assessment.

1. The Fuel System

The A-20 does have some vulnerability reduction features inherent in it's design, such as foam in the wing tanks, fuel feed line redundancy, motive flow, a "get home fuel" compartment in the main feed tank and the majority of the plumbing on the interior of the tanks. The A-20's greatest fuel system design flaw is the location of the the fuel tanks. Ball [Ref. 2], presents an analysis of this problem on pages 203-204. The A-20's longitudinal transfer tanks present too much exposed surface area; and as seen from the single hit vulnerability assessment, the forward feed tank is located in a position where engine fuel ingestion caused by fragment penetration can have catastrophic results.

2. The Propulsion System

The A-20's propulsion system does have redundancy in the engines and mounting system. The major flaw in it's design is with it's location adjacent to a fuel tank (See

Ball [Ref. 2:pp. 214-215]). The inlet duct is situated such that fuel ingestion with resultant engine fire is a possibility. On the other hand, the inlet ducts are mounted in such a fashion that they are shielded from ground fire.

3. <u>The Flight Control System</u>

The A-20's flight control system is multiply redundant. It is unusual in that it has a complete mechanical backup to the AFCS. The component placement of the hydraulic reservoirs which store the fluid to actuate the flight control surfaces is a weakness of the A-20 design. The main reservoirs are located beneath the engines with the majority of surface area vulnerable to ground fire. Ball [Ref. 2:pp. 199-200] writes about the positioning of critical components to where they are shielded and kept away from any component that might contribute to cascading damage, such as hydraulic fluid finding its way onto the hot engine.

4. <u>The Crew System</u>

The A-20 carries no armor for the pilot (See Ball [Ref. 2:pp. 220-221]). For the type mission it is designed for, armor might be a viable tradeoff to reduce the pilot's installed P<k/h>. The cockpit location in the vertical plane is also a design feature that needs some work. The height at which the pilot sits presents more exposed body

surface area than desired. There is room to lower the cockpit in the design configuration.

All of these vulnerability reduction features (and others), were considered when the author was performing a second iteration on the A-20's design. The second iteration of the A-20 is shown in Figure 8.10. Notice how the intake has been moved aft, away from the forward fuel tank and also the possibility of cannon exhaust ingestion. The cockpit has been lowered, and, although not visible, there are spall shields in the cockpit. Part of the fuselage, just aft of the pilot has been more aerodynamically shaped to provide for better airflow to the inlets (And a possible reduction in the aircraft's radar cross section). This has also resulted in a reduction of frontal area. Another feature worth investigating is the feasibility of 2-D nozzles as shown in the figure.

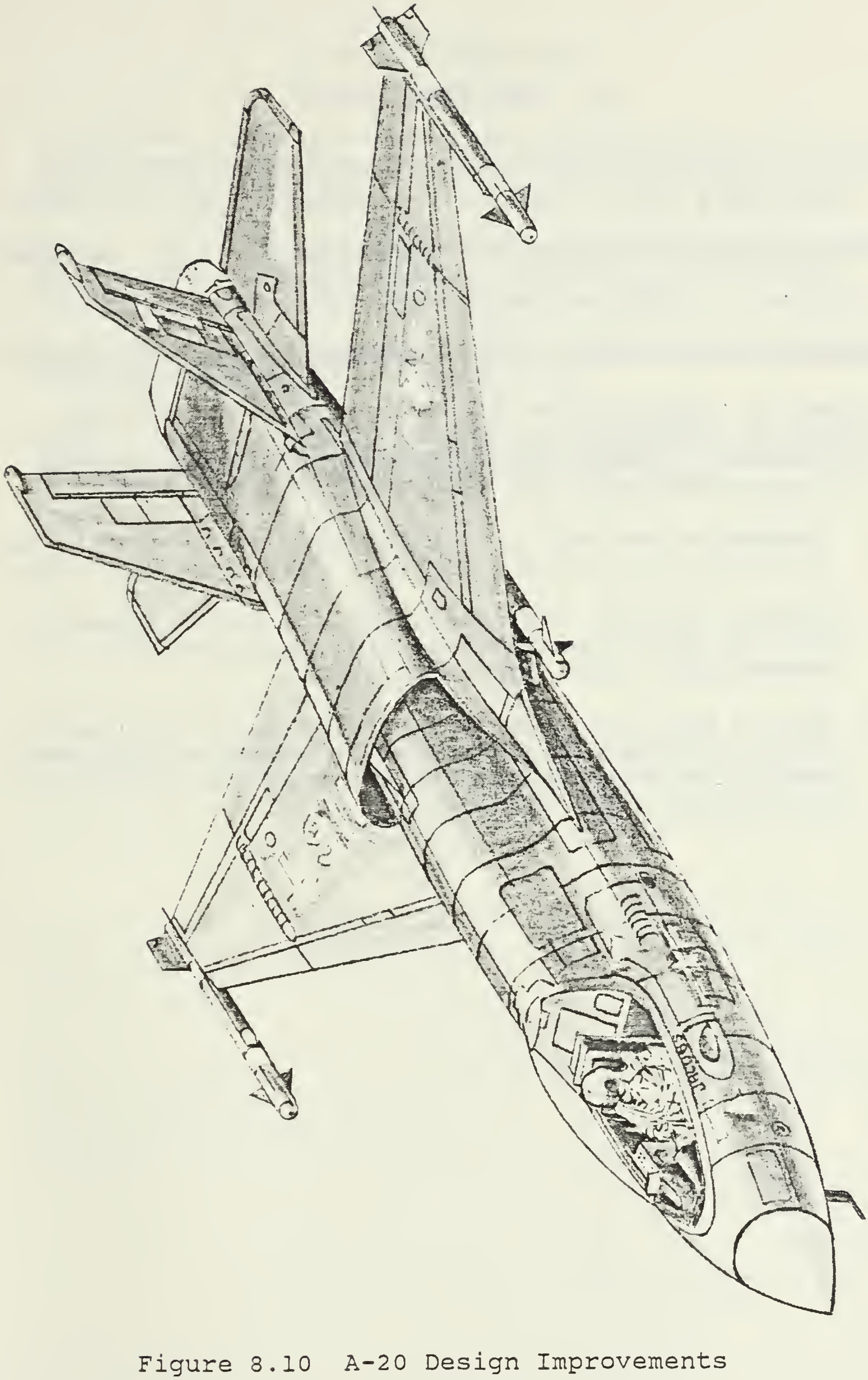

Figure 8.10 A-20 Design Improvements

IX. RECOMMENDATIONS

The single hit vulnerability assessment and the steps leading up to it are just the first ones that are necessary to produce the complete methodology of a survivability assessment. The following are recommendations for follow on areas of concentration to complete this assessment:

1. Produce a methodology addressing the multiple hit vulnerability of the A-20 [Ref. 2:pp. 169-180].

2. Determine the A-20's vulnerability to internally and externally detonating warheads [Ref. 2:pp. 183-191].

3. Produce a case study assessing the A-20's susceptibility (RCS, IR radiation, etc.) using Ball's methodology [Ref. 2:pp. 227-311].

4. Tie in both the overall vulnerability and susceptibility assessments to produce a scenario dependent overall survivability assessment of the A-20 (See Ball [Ref. 2:pp. 316-337]).

LIST OF REFERENCES

1. Department of Defense Military Standard MIL-STD-2069, Requirements For Aircraft Nonnuclear Survivability Program, 24 August 1981.

2. Ball, R.E., The Fundamentals of Aircraft Combat Survivability Analysis and Design, American Institute of Aeronautics and Astronautics, Inc., 1985.

3. Department of Defense Instruction 5000.2, Major Systems Acquisition Process, 19 March 1980.

4. Raymer, D.P., Class Notes--AE 4273 Aircraft Conceptual Design, Department of Aeronautics, Naval Postgraduate School, Monterey, California, January 1986.

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